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Application of artificial neural networks and colored petri nets on earthquake resilient water distribution systems

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APPLICATION OF ARTIFICIAL NEURAL NETWORKS AND COLORED PETRINETS ON EARTHQUAKE RESILIENT WATER DISTRIBUTION SYSTEMS

by

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ABSTRACT

Water distribution systems are important lifelines and a critical and complex infrastructure of a country. The performance of this system during unexpected rare events is important as it is one of the lifelines that people directly depend on and other factors indirectly impact the economy of a nation. In this thesis a couple of methods that can be used to predict damage and simulate the restoration process of a water distribution system are presented. Contributing to the effort of applying computational tools to infrastructure systems, Artificial Neural Network (ANN) is used to predict the rate of damage in the pipe network during seismic events. Prediction done in this thesis is based on earthquake intensity, peak ground velocity, and pipe size and material type. Further, restoration process of water distribution network in a seismic event is modeled and restoration curves are simulated using colored Petri nets. This dynamic simulation will aid decision makers to adopt the best strategies during disaster management. Prediction of damages, modeling and simulation in conjunction with other disaster reduction methodologies and strategies is expected to be helpful to be more resilient and better prepared for disasters.

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1. GENERAL INTRODUCTION

Though the world is becoming smaller and smaller thanks to rapid developments in various sectors, systems are becoming increasingly complex whether it is telecommunication, transportation, power or water distribution systems. This complexity may be due to the increase in number of components, physical scaling, or due to increased interdependencies among various components. The complexity further increases when these infrastructures are subject to natural or manmade disasters.

In recent years much has been learned from natural disasters and risk to infrastructure systems. It is estimated that, the total direct economic loss from natural catastrophes during the decade of 1987-1997 was 700 billion USD, an average loss of 70 billion USD per year. Increasing population concentrations and fragile infrastructures in hazard prone areas are the main causes of the increased catastrophes costs (Munich Re 1998a). Among these catastrophes, earthquakes are responsible for 15% of the total number of events, and 30% of the total damage (Munich Re 1998b). Earthquake induced damage is related to the physical vulnerability of network components. The ideal situation of making all components seismic resistant might be technically possible, but is practically infeasible for economic reasons.

Research has been done in the field of earthquake engineering to improve the performance of infrastructure systems by, for example doing seismic analysis of building, bridges and other structures. Damages to these civil infrastructures can result in tremendous socioeconomic impacts. According to Dong, (2002), traditional and conventional earthquake engineering cannot meet the growing demand for effective seismic mitigation strategies. Risk management of utilities is more complex and far reaching than current methods can handle. By adopting smart strategies, utilities can improve performance but they require more comprehensive approaches and better tools, which can be used effectively by their workforce (Grigg 2003).

Past experiences show the importance and necessity of studying the performance of water systems during and after an earthquake. Relatively few companies have disaster plans that are developed to address a situation imposed by a large earthquake. Also, due to lack of experience, particularly outside California there is a need to develop effective methods to evaluate and exercise the plans (Schiff and Tang 1995). Predicting and anticipating the performance during such events combining multidisciplinary knowledge and advanced computational and simulation tools is also important. It is desirable to develop effective analytical methods and tools to predict possible damages under different earthquake scenarios (Dong 2002). In other words, for a given water system it is desirable to know in advance the system's performance and its operation status following an earthquake event. Replacement cost of utilities is higher relative to the cost of retrofitting the existing lines. Also the concern is if an earthquake occurs shortly after the replacement and incurs damage which will lead to unduly criticism. (Schiff and Tang 1995). This too points to the importance of using the prediction and forecasting tools, and being knowledgeable about the future to the greatest possible extent and taking action accordingly.

Simulating and analyzing different anticipated system condition will aid in making decisions about system upgrades, hazard mitigation, and disaster reduction planning (Shinozuka 2002). In addition, modeling the restoration process and response to natural or deliberate disruptions, can help in estimating monetary losses as well. This is because models can allow mapping of failed components with repair costs by embedding network component correlation in their formulation. A number of studies have looked at work flow scheduling, resource management in workflows, and scheduling using constraint satisfaction techniques. However there is not much research published regarding the simulation of workflows, depicting real restoration process and resource allocation of water distribution systems impacted by earthquake.

In cooperation with the Federal Emergency Management Agency (FEMA), the Technical Support Working Group has developed a system called Pipeline Net that can calculate, locate, and map the population at risk from the introduction of contaminants to the public water supply. This modeling method which integrates EPANET and Arcview help assess the risk to public water supplies. However this may not be of much use in the disaster management after a disaster like earthquake, because for physical damage simulation of interconnected components, the flows of activities are more important to bring the system into the previous level performance. So a general systems modeling language like SysML and simulation tool like Colored Petri nets that can model a general system can be more useful for modeling the activities after a seismic event.

A number of diagrams in Sys ML can be used to completely represent a system and is shown in Figure 1.1 Sys ML is a domain specific modeling language for Systems Engineering that can model a wide range of systems, including hardware, software, information, processes, personnel, and facilities.

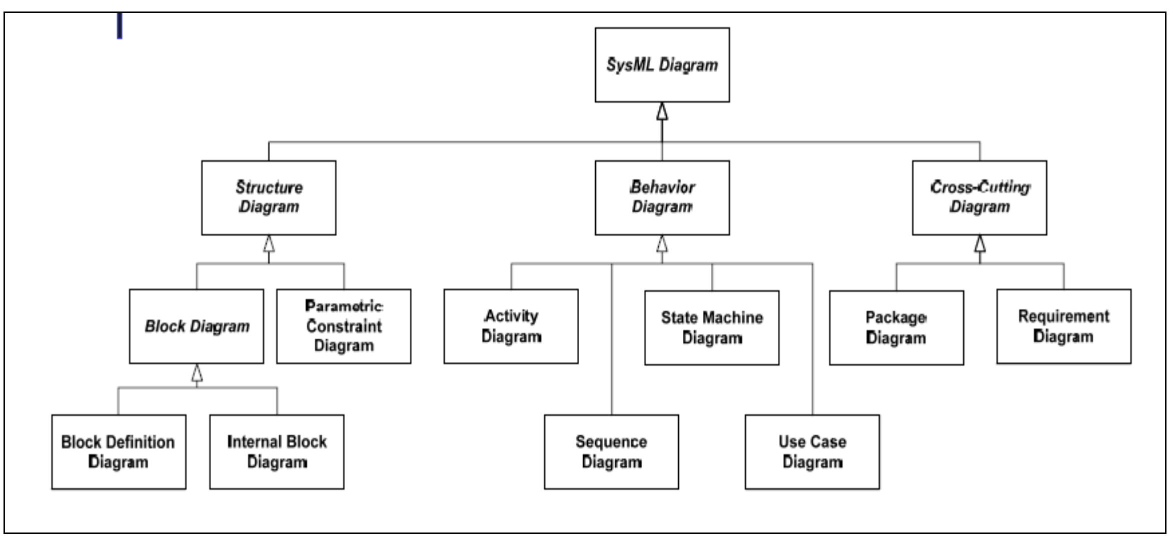

FIG. 1.1. System Modeling Diagrams (www. Sysml.org)

The possible interdependencies of a water distribution system during an earthquake scenario are represented using a top level use case diagram in Figure 1.2. According to Bittner and Spence, (2002) described in page xvi, "Use cases, stated simply, allow description of sequences of events that, taken together, lead to a system doing something useful”. Use case diagrams describe the basic functionality of the system and interaction with its actors, Also use cases are a means of communicating to users and other stakeholders what the system is intended to do. The system can be represented using the Department of Defense Architecture Framework (DoDAF) and is given as Appendix C.

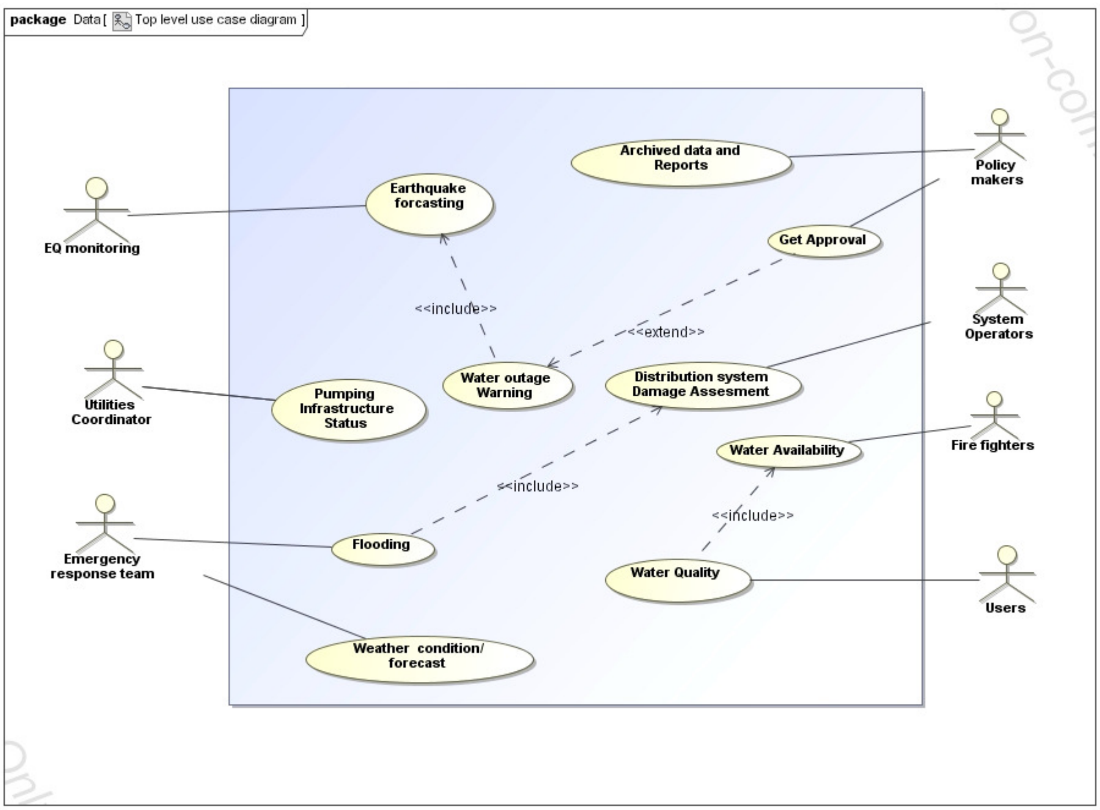

FIG.1.2 Water System in Earthquake Scenario- Use Case Diagram

The "include" relationship provides a mechanism for factoring out common functionality which is shared among multiple use cases. The "extend" relationship provides optional functionality, which extends the base use case at defined extension points under specified conditions.

In a water system, the distribution lines are vulnerable to earthquake damage and compromising system performance. Therefore a computational tool, such as, Artificial Neural Networks (ANN), are used to predict the damage / repair rate in seismic events and Colored Petri nets (CPN) are used to model the restoration process and simulate the restoration curves. An artificial neural network (ANN), often just called a Neural Network (NN), is a mathematical model or computational model based on biological neural networks. It consists of an interconnected group of artificial neurons and processes information using a connectionist approach to computation.

Colored Petri nets are a discrete event modeling language combining Petri nets with the functional programming language Standard ML. It is extensively used for modeling and it is primarily used for studying the dynamic concurrent behavior of network based systems where there is a discrete flow. Petri nets provide the foundation of the graphical notation and primitives for modeling. Standard ML provides primitives for the definition of data types, for creating compact and parameterisable models. (Jensen et al. 2007). Places, transitions and arcs form the basic structure of a Petri Net, places and transitions are the nodes and the arc connects from a place to a transition or a from a transition to a place. There can be zero or more tokens at a place. Petri nets represent a system, through the use of graphical representations called transitions, places, tokens and arcs. A system explained by an ‘event’, ‘actor’, ‘task’ may be represented by a transition in a Petri net. The token or object in this graphical language can represent physical objects or conceptual objects such as policies.

One of the properties of Petri nets is sequential execution, which means, for example if a transition T2 is following a transition T1 in Petri net network, T2 can fire only after the firing of T1. Another property of Petri nets is synchronization by which if there are two input places connected to a transition, that transition will be enabled only when there is a token at each of its input places. In 1962, Carl Adam Petri, originally proposed Petri nets with out any notion of time. In the 1970s time was added in order to analyze the performance of modeled system. Colored and timed Petri nets are extension of classical Petri nets and represented in Figure 1.3.

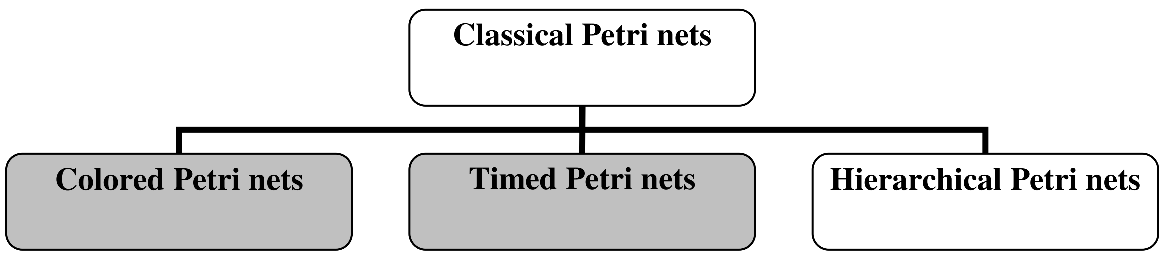

FIG.1.3. Extension of Petri nets

The research is presented as two different papers in this thesis. The broad objectives are to 1) Use artificial neural network to predict the damage rate of water distribution lines during seismic events. 2) Demonstrate the application of colored Petri nets for post earthquake restoration modeling and 3) Develop a earthquake restoration model for the trunk lines of a water distribution system.

PAPER

1. PREDICTION OF DAMAGE/REPAIR RATES IN WATER DISTRIBUTION SYSTEMS DUE TO SEISMIC EVENTS USING ARTIFICIAL NEURAL NETWORK

ABSTRACT

Water distribution systems are important lifelines that can be affected by natural disasters, such as earthquakes. It has been reported that it takes one to two weeks or more to restore the water distribution system to a fully functional level after a major earthquake strikes. So, it would be beneficial to society if one could predict the damage/repair rate experienced by the water distribution system. These predictions can be used by city planners or developers to identify the weak sections in the system and to improve its resilience. In this paper, feed forward back error propagating multilayer neural network is used for the prediction and it is trained using the damage statistics available for different earthquakes in twelve different locations. The training was done using earthquake magnitude, pipe diameter and material type, and peak ground velocity (PGV) as input parameters and the damage/repair rate per thousand ft as output parameter. The output of the neural network model was compared with two other empirical formulae and the results were found to be promising.

INTRODUCTION

Water delivery systems, particularly underground pipelines, can be severely damaged by strong ground motions during earthquakes. In addition to the direct impact on the system, such as interruption of water supply and inadequate supply for fire fighting, there will be other consequences such as pressure head losses, subsequent loss of water service, water pumping and hauling costs, and erosion of roadway subgrades due to leaks and spills, which can be detrimental to the local community. Other potential adverse consequences include flooding of roads and nearby basements and damage to adjacent utilities and foundations (Hong 2006). In 2001, the US Environmental Protection Agency (EPA) released a national survey of drinking water infrastructure needs which concluded that approximately 151 billion dollars would be needed over twenty years to repair, replace, and upgrade the nation's 55,000 community drinking water systems to protect public health (ASCE 2005). Upgrading the distribution system is a strategy adopted by authorities to reduce potential damage, and often the first step in the seismic upgrade of a pipeline system is the evaluation of the likely damage in the existing system due to earthquakes (O'Rourke and Deyoe 2004).

During seismic events, multiple pipelines in a water distribution network are damaged simultaneously and, due to the complex nature of the physics affecting pipe damage under seismic waves, damage assessment is something that still remains challenging (Dong 2004). This paper uses the Artificial Neural Network (ANN) method to predict the damage/repair rates in water distribution systems due to seismic events. Artificial neurons are typically nonlinear, and this is especially an important property when the physical process of interest is absolutely nonlinear (Ham 2001). The term damage/repair rate is used herein since most databases available consist of a record of the repairs to restore the systems, and repair records are inherently associated with the damages caused by the earthquake event.

In many cases the data regarding damage to water distribution systems are expensive to collect, incomplete, or unavailable (Allouche and Bowman 2006). However, ANNs can tolerate missing data and still make reasonable predictions (Brawley 1993). The trained network can be used for different earthquake scenarios to minimize the damage to an existing network or to decide upon the pipe material type and diameter when laying out a new distribution network. Also, the results of the network can be used by government agencies while prioritizing the pipeline sections in the system for rehabilitation and can aid in the restoration activity. This method is envisioned for use in conjunction with other methods to give an accurate damage/repair rate for the scenario of interest.

DATA BASE DESCRIPTION

The data used for the ANN training was taken from the Part 2-Appendices of the report entitled "Seismic Fragility Formulations for Water Systems", which was published in April 2001 by the American Lifelines Alliance. (ALA 2001) This Alliance is a public-private partnership between the Federal Emergency Management Agency (FEMA) and the American Society of Civil Engineers (ASCE). The various earthquakes that have been considered for this study and their respective magnitudes are given in Table 1. Four parameters that have a major impact on the distribution pipelines, pipe material type, pipe diameter, earthquake magnitude and peak ground velocity (PGV) were used to train the ANN. These parameters are not necessarily exhaustive, but are certainly significant factors based on review of relevant literature (PAHO 2007; Pei Zongchang et al. 2005; O'Rourke and Jeon 1999) that can influence the damage to the distribution system in a seismic event. The magnitude of the earthquakes (measured on the Richter scale) varied from a low of M=6.3 in the 1933 Long Beach earthquake to a high of M=7.9 in the 1923 Kanto and 1968 Tokachi-oki earthquakes. The pipe material type used in these distribution systems consisted of ductile iron, asbestos cement, steel, concrete pipe, cast iron, and in some cases a combination of these materials. The pipe diameters were divided into three categories namely *large* (> 12 in/~30.48 cm.), *small* (≤12 in.) and *Distribution Systems* (DS). The Distribution system consists of mostly small diameters, but may include some large diameters also. Peak Ground Velocity (PGV) was recorded in in/sec at each of the sites considered. Data in which the wave propagation is measured using peak ground acceleration (PGA) and Modified

Mercalli Intensity (MMI) were omitted to maintain consistency in data used in training. O'Rourke and Toprak (1997) carried out a study based on the 1994 Northridge earthquake and found that the zones of highest PGV show a spatial correlation with the damage/repair rate concentrations.

THE NEURAL NETWORK MODEL

A three layer back error propagating neural network model which has one input layer, one output layer and a hidden layer was used in this study Though not always practically feasible, Hornik et al. established that an Multilayer Perceptron Neural Network (MLP NN) that has only one hidden layer with a sufficient number of neurons can act as a universal approximator of nonlinear mappings (Ham and Kostanic, 2001). A supervised learning algorithm which was provided with a set of input and target values was used to train the network. Initially, the training was done using only two input parameters, the earthquake magnitude (M) and PGV, assuming they were the main physical variables affecting the phenomenon. However the training did not prove to be very successful, as the goal of 0.0001 MSE could not be achieved even after 10,000 epochs. Increasing the number of hidden neurons was also attempted, but it did not show significant progress in reducing the error and achieving the target.

Consequently, the pipe diameter and material type were included in the training and the number of hidden neurons was optimized to produce a minimum error. Including those two parameters significantly improved the training and the network achieved its goal in less than 100 epochs, which shows that those two parameters influence the damage/repair rates. From a data set of eighty, sixty four were used for training; the remaining 16 were used for testing. The Tansig transfer function was used in the hidden layer and Purelin in the output layer, both of which are commonly used transfer functions. Eighteen neurons in the hidden layer performed best, which resulted in an average prediction error of fifteen percent. Training results are shown in Figure 1 while Figure 2 shows the testing results; the errors are reasonable and acceptable.

Performance Analysis

The developed network was analyzed by comparing the predicted value and actual damage/repair rates. The network was also analyzed for its performance by comparing with the empirical wave propagation fragility developed by O'Rourke and Jeon (1999) and also with the one developed by the American Lifeline Alliance (O'Rourke and Deyoe 2004). O'Rourke and Jeon (1999) developed an empirical relationship using data from the 1994 Northridge earthquake, whose formulation has the following form:

$$RR = \left(\frac{V_{max}}{266}\right)^{1.22} \qquad (1)$$

The American Life Alliance project developed the following wave propagation damage relation based on an analysis of 81 data points from 12 earthquakes,

$$RR = 0.0024\ Vmax \qquad (2)$$

where, RR = the repair rate in damage/repairs per kilometer,

Vmax = the peak horizontal velocity (PGV) in cm/sec

The same set of data was used in all the three cases to facilitate comparisons. Table 2 shows the percentage error noted in the estimation of the damage/repair rates using equations (1) and (2) and also the prediction error of the network model developed.

The results show that the neural network prediction is comparable with other methods and can be used for the prediction of damage/repair rates with reasonable accuracy. As the empirical formula is based on only one of the variables, PGV, any error in recording that value might result in incorrect estimation of the damage rates, while the ANN model uses a number of contributing factors which will tolerate the missing and misrepresented data and still do a reasonable prediction. So, the ANN model can be effectively used in conjunction with other methods to get a more reliable picture of the potential damage scenario.

CONCLUSIONS

In this study a feed forward back error propagating multilayer neural network was used to predict the damage/repair rate of buried pipelines in water distribution systems for different earthquake scenarios. The observed error in predicting the damage/repair rates might be attributed to input parameters not included such as corrosion data. For example, corrosion is thought to have had an influence on the damage rate in the 1983 Coalinga earthquake. Similarly, sample size is also important in the wave propagation damage statistics, which means that, small damage/repair rates require data over a large length of pipe to enable good confidence in the data. If these factors are considered for and incorporated into the training, the neural network proves to be a promising methodology for the prediction of the rate of damage/repair of buried pipelines in water distribution systems.

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Table 1. Earthquakes whose Data used for Network Training

Year	Place	Magnitude
1923	Kanto, Japan	7.9
1933	Long Beach, CA	6.3
1964	Niigata, Japan	7.5
1965	Puget Sound, WA	6.5
1968	Tokachi-oki, Japan	7.9
1971	San Fernando, CA	6.7
1979	Imperial Valley, CA	6.5
1983	Coalinga, CA	6.7
1989	Loma Prieta, CA	6.9
1989	Mexico	7.4
1994	Northridge, CA	6.7
1995	Hyogoken-nanbu, Japan	6.9

Table 2. Performance Comparison

Method	Percentage Error
Empirical Equation (O'Rourke)	13.01
Empirical Equation (American Lifeline Alliance)	13.96
Neural Network Model	14.99

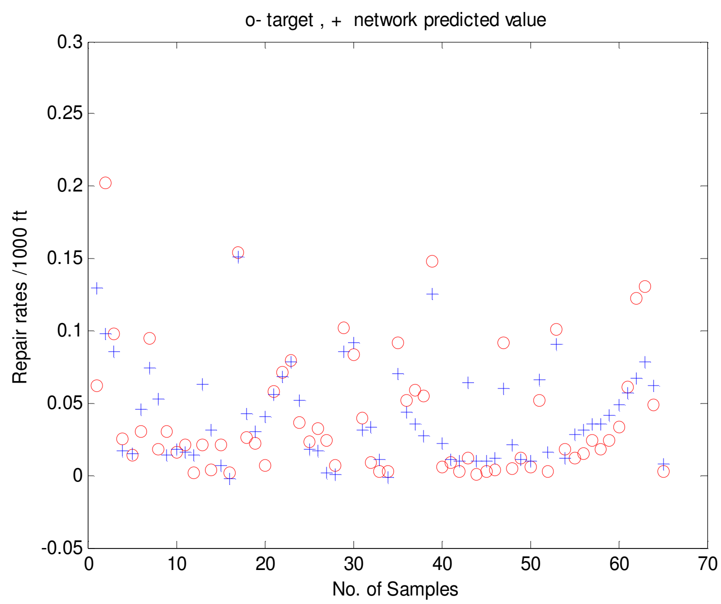

FIG. 1. Training Results of the ANN for Water Distribution Systems

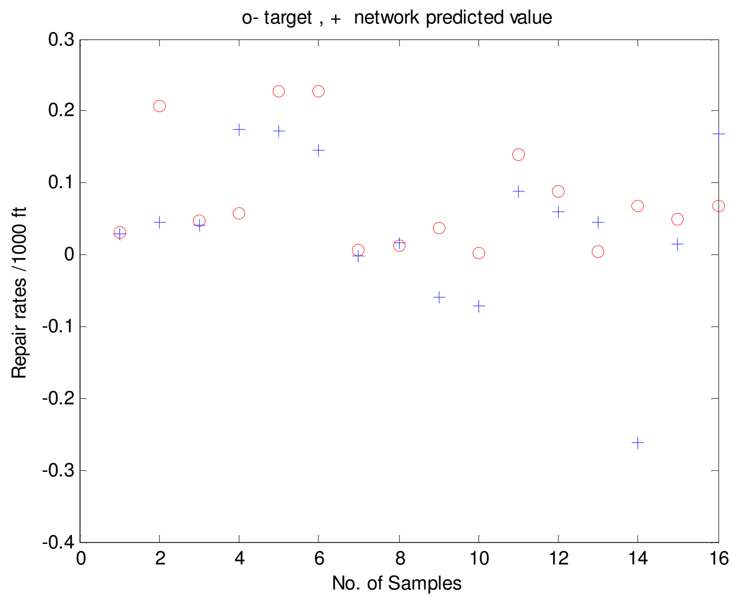

FIG. 2. Testing Results of the ANN for Water Distribution Systems

2. POST EARTHQUAKE RECOVERY OF WATER SYSTEMS: DISCRETE EVENT SIMULATION USING COLORED PETRINETS

ABSTRACT

Planning and preparedness is essential for any resilient infrastructure system. Modeling and simulation give engineers and planners a better understanding of the system and helps them make better decisions. The objective of this study is to demonstrate an improved model for disaster restoration process, using discrete event simulation approach. The study also aims to help improve the post earthquake restoration process by simulating restoration curves. In this paper Colored Petri Nets (CPN) are used to model the system and simulate its behavior. Resource allocation after a rare event like an earthquake differs from the resource allocation of projects and processes in that the requirement and the time taken to do the repair/recovery is not known before hand, and also the priorities might change in different operational plans/strategies. The trunk network of Tokyo water distribution system is taken as an example to present the scenario to model the restoration process. Timed simulation allows visualizing the restoration progress, which is usually depicted as a restoration curve. The results on the restoration time are presented based on multiple simulations.

INTRODUCTION

Lifeline infrastructures are a sector in industry that requires year round attention and vigilance. These infrastructures are complex interconnection of electrical, mechanical, electronic components to name a few. A water distribution system for example, is a complex combination of pipe networks, electric systems, pumping systems, tanks and a number of software controlling all these. The safety and security standards of this century requires tools that are capable of analyzing and understanding infrastructures in large-scale disasters involving a multitude of components and associated complexities. Also they can turn out to be incapable when a large natural disaster like an earthquake strikes. It would be advantageous to utilize the computational and modeling tools that have been developed to effectively and efficiently handle the situation. Nowadays, using computer science and information technology to support decision making skills and enhance problem solving abilities is widely recognized as a novel direction to help manage large scale environmental emergencies. (Cortes et al. 2000).

The extent of structural and functional disruption following an earthquake and similar disasters depends on factors like the site geology and soil conditions, the location, the strength of infrastructure, and the intensity of the damaging forces. The structural damage caused to the infrastructure can be called the hard damage and the cessation and the slowing of the functions of various systems caused by hard damage can be called soft damage. (Isumi 1985). Depending on the importance of the component and its location in the network, even a small hard damage, may lead to soft damage large enough to stop all functionality, in this case getting water delivered to the points of interest.

Functional disruption and its associated impacts on infrastructure performance are important for a number of reasons. These functional disruptions are directly related to the business activities, which have a profound effect on economic activities, some other times it may required for the calculation of total losses in these events. It will be useful in taking operational decisions and also while planning infrastructures. According to Chang et al. (1999) in addition to causing repair costs, the functional interruption, the physical damage disrupts the normal economic activities. While assessing the economic loss due to the disruption, duration of the functionality loss is as important as the spatial extent and its severity. One of the factors on which the resilience of a community is depends is the rate at which functionality can be restored after an earthquake. (Çagnan et al. 2006).

Post-disaster repair and system restoration modeling is one of the critical gaps in modeling the economic impact of earthquakes (Chang et al. 1999).The pace and sequence of the restoration process has impact on business interruption which in turn have a profoundly affects a nation's economy. Resources are a crucial part of disaster management, particularly of restoration process, because they are the basis of taking actions to respond to or preparing for environmental emergencies (Liu 2004). Because time, quantity and quality of the resources are limiting factors, emergency managers have to try different prioritization strategies to assign resources in space and time to the damage locations and improvement can result by using computer based decision support systems. (Fiedrich et al. 2000). An effective method to evaluate restoration process will be helpful since the duration of functionality loss also important as spatial extent of disruption. Considering the reasons mentioned above a timed computer modeling and simulation will be the one that will be apt for the situation

Damage in Past Earthquakes

In 1995 a M=6.9 earthquake struck the Osaka Bay in Japan, causing damage to pump discharge lines of the city of Kobe. It took 12 days to repair these main lines, and complete restoration of the Kobe water distribution took over two months (1,200-1,500 repairs). The M=7.7, 1999 Chi Chi earthquake caused an interruption of potable water service to 360,000 households in Taiwan. An estimated one million people lost access to potable water in the 2001 Kutch earthquake (M=7.7) in India. (Scawthorn et.al. 2005).

In the 1989 Loma Prieta earthquake, the San Francisco water department experienced 70 water main breaks and 50 service line breaks. The East Bay municipal utilities identified over 1,290 water pipeline breaks following the earthquake, including a 60 inch raw water pipeline supplying water to a filter plant. The San Jose water company reported 155 breaks, 67 of which were repaired in first 48 hours. (Dames and Moore 1999). In the 1994 Northridge earthquake Los Angeles Department of Water and Power's water system facilities incurred extensive damage throughout San Fernando Valley and in the Sherman Oaks area. There was also localized damage to water supply systems in West Los Angeles area and throughout the eastern San Fernando Valley. Immediately following the earthquake, approximately 100,000 customers were without water. Within 5 days, water service was restored to all but a few thousand customers; after 10 days, less than 100 scattered customers were without water. The Department of Water and Power estimates that repairs of earthquake damage to the city's water system cost approximately $40 million (Aurelius 1994). Seventy four trunk line repairs were made in the San Fernando Valley, and mostly occurred in steel pipelines, with 80% of all repairs in riveted and continuous wall steel piping. Sixty-six percent of repairs were in continuous wall steel pipe, whereas only 56% of all trunk lines were composed of this type of pipe (O'Rourke and Toprak 1997).

Review of Literature

The different approaches previously used in modeling post earthquake life restoration include (1) statistical restoration curves approach, (2) deterministic resource constraint approach, (3) discrete state, discrete transition Markov process and (4) network approach (Çagnan and Davidson 2007).

In statistical restoration curve approach, expert opinion based on previous experiences is utilized to develop a restoration curve. Gamma distributions are used as restoration curves in the work done by Nojima et al.(2001) where the parameters of the distributions are estimated as a function of damage level using data from previous earthquakes. According to Chang et al. (1999) the disadvantage of this method is that issues such as manpower constraints and the possibility of speeding up of the restoration process is not effectively modeled. Aid from other sources, for example from nearby counties or from the government cannot be effectively modeled in this method. In a research carried out by the Applied Technology Council (ATC), the number of repair days required to reach 100 percent capacity was estimated based on ground shaking intensity, Modified Mercalli Intensity (MMI), facility type, and region of the US (ATC 1992).

In the deterministic resource constraint approach, the restoration model is developed based on assumptions like number of service personnel available and accordingly the time period required for the complete restoration is modeled. This approach has the advantage of being able to depict the restoration progress both in time and space to a certain extent. The downside of this method is that, since the restoration processes are modeled deterministically, the uncertainty associated with activities like the restoration time is not effectively modeled.

The challenge of modeling the restoration processes as a discrete state, discrete event Markov process is that model parameters and the associated probabilities need to be estimated accurately. Isoyama et al. (1985), Iwata (1985) Kozin and Zhou(1991)and Zhang(1992) used this approach in their studies.

In the network approach system consists of supply and demand nodes and these are connected by links. For example, in the work by Nojima and Kameda (1992) graph theory and optimization theory were combined to derive optimal restoration process and minimum spanning trees methodology to output repair sequences. The system has to be simplified to model the evolution of restoration in this approach. (Çagnan and Davidson 2007).

In empirical based approach, the restoration time is modeled as a function of available resources for post disaster damage repair. Research by Ballantyne (1990), estimates of unit repair time were developed, specifically that one repair crew could fix 2 pipe leaks or one pipe break per 12 hour shift, assuming a fixed number of repair crews following a disaster. He also assumed more severe resource constraints while modeling disasters of higher order since other supporting facilities such as telecommunication, transportation, electric power are also likely to be disrupted, affecting the restoration process. Ballantyne also gave twice as much as priority to business districts and industrial areas than to other areas of the city which is quite reasonable.

Çagnan et al. (2006) used discrete event simulation to model post-earthquake restoration processes of electric power systems, which can either be deterministic or stochastic. This method considers the damage state and the available resources. Çagnan et al. modeled the elements as entities (transmission substations and power plants), resources (repair teams), events (repair), and variables (damage state). A commercially available Promodel software package was used for the simulation.

Approach Used

The discrete event simulation approach described herein adopts features of the research described above and adds some improvements. It is similar to the empirical based approach of Ballantyne (1990) in that it accommodates dynamic variations like change in the number of crew during the restoration process. It also incorporates other decision variables such as repair prioritization plan and variation in the availability of resources. The introduction of external resources from nearby areas or due to mutual aid agreements is an example for the variability in availability of resources.

This study focuses on simulating the restoration process using a discrete event approach, one the first few applications of discrete event simulation to the post-earthquake restoration problem of water systems. This restoration modeling approach enables the explicit representation of real life restoration processes. The timed restoration process can be monitored at any desired stage of the simulation which is not usually possible in the conventional simulation methods. For example, the stage and time of resource depletion can be monitored and can be recorded in a file, which will help in analyzing situations and making various decisions, such as those about storage of resources. This simulation will also help improve the estimation of restoration time required to estimate the economic loss due to business interruption caused by water outages. This in turn, will indicate the need to improve the restoration process for future anticipated earthquakes.

Restoration curves are usually plotted for a particular location or event mostly from previous data or from past experiences, for example the restoration curves plotted in ATC-13 (ATC 1985). With the simulation, restoration curves can be plotted for range of events, different magnitudes of earthquake and various resource capacities. The effect of mutual aid agreements on restoration time and the preparedness of utilities for a impending disaster can also be evaluated. Reallocation of resources or additional preparation required restoring the system within a predetermined timeframe and related monetary limitations can be estimated. Recent predicting / forecasting tools and methodologies in combination with the proposed simulation can help to be better prepared for these rare events.

Domain-specific software may not always be sufficient to model and simulate the system, particularly when the system interacts with external events. For example, when modeling a water distribution system, the domain specific software can model the network, simulate many scenarios like fire and pump speed, and can even animate the system. But that may not effectively model events outside the system, such as the failure of service vehicle, which might affect the total time taken for system recovery. A general system modeling language/ tool can show the interdependencies between various components of the system, can indicate the effect on the system when certain components are removed, replaced or get damaged. For these reasons we use Colored Petri Nets (CPN) to model and dynamically simulate the system.

Colored Petri Nets (CPN)

CPN is a graphical oriented language for the design, specification, simulation, and verification of systems. It is particularly well suited for systems in which communication, synchronization, and resource sharing are important (Jensen 2007). The specification for a system can be verified using different mathematical techniques and tools. CPN is one of the formal specification techniques that can be used to model the system's behavior and check its correctness by analyzing liveness, boundness, and deadlock properties (Jensen 1992).

This graphical and mathematical modeling tool has been applied in many areas like schedulability analysis (Tsai et al. 1995), modeling infrastructure interdependencies (Gursesli and Desrochers 2003), failure and safety analysis of systems (Adamyan et al. 2002), reliability analysis (Kavi et al. 1995) and many industrial applications like security and access control of systems (Rasmussen and Singh 1996), to name a few. No significant work has been done using CPN for disaster management of infrastructure systems.

CPN can model a system through the use of a few graphical representations named places, transitions, tokens, and arcs. Places are represented by circles or ellipses, transitions by rectangles, and arcs by directed arrows. The directed arc runs between places and transitions. The arc expressions describe how the system changes when transitions occur. The token or object in this graphical language can represent physical or even conceptual objects. The features or characteristics that are explained by 'event', 'actor,or 'task' in a system may be represented by a transition in a Petri net. (Hee 1994).

CPNs can be used as a visual communication aid, similar to flow charts, block diagrams, and network diagrams. A feature that differentiates Petri nets from other modeling tools is the use of tokens to simulate the activities in the system. Also state equations, algebraic equations, and other mathematical models can be used in Petri nets to describe or simulate a system's behavior (Kumar and Ganesh 1998)

The formal definition of a Petri Net is given in a paper by Murata (1989)

5-tuple representation of a Petri net is ,

$PN = (P, T, F, W, M_0)$

where

$P = \{p_1, p_2 ...... p_m\}$, a finite set of places

$T = \{t_1, t_2 ...... t_n\}$, a finite set of transitions

$F \subseteq (PxT) \cup (TxP)$ is a set of arcs (flow relation)

$W : F \to \{1,2,3....\}$ is a weight function

$M_o : P \to \{0,1,2,.....\}$ is the initial marking,

$P \cap T = \emptyset$ and $P \cup T \neq \emptyset$

A Petri net structure without any specific initial marking is denoted by $N = (P, T, F, W)$ and with given initial marking is denoted by (N, M_o)

When the original Petri nets were introduced it did not have the notion of time. Later, dynamic systems and various scheduling problems necessitated the introduction of timed Petri nets. By means of colors, data can be specified and timed Petri nets can be considered an extension of colored Petri nets, with time as a special color (Mulyar and Aalst 2005). One of the advantages of using Colored Petri nets for the simulation is that it will record the events that trigger the activities. It also helps to visualize which activity is taking more time and the constraining resource causes it. Factors like interdependencies, conflicting priorities, and substitution of resources which have an influence on overall resource allocation and management can be represented using Petri nets (Kumar and Ganesh 1998).

Timed CPN

Even though many CPNs are used to check the logical correctness of a system, they can also be used to investigate its performance, e.g., maximum time used for the execution of certain activities, average waiting time of certain requests, etc. (Jensen 1992). The time factor is important when restoring water after a seismic event and the time taken to recover is depends on the extent of damage, resources available, and also on the priority assigned to the work. For this kind of analysis CPN model is extended in which time concept represented by a continuous or discrete global clock. This is done by allowing the token to carry a time stamp in addition to the token color.

Emergency Management

The restoration process of an infrastructure system after a major disruption falls within the category of emergency management. The importance of having a functioning water system after natural disasters, including earthquake is as follows
(ASCE, 1997)

- For emergency medical , public safety and emergency operating centers
- For emergency drinking water , food preparation and sanitary purposes
- For fire suppression, including high rise structures
- For restoration of business and industry for economy and employment
- For minimization of damage from flooding to other facilities

Cuny (1983) pointed out that it is very important for developing nations to work on infrastructures in the process to achieve effective emergency management. Regardless of a nation's economic status, once a disaster strikes, emergency managers take certain steps to restore the systems. The process of emergency management involves four phases: mitigation, preparedness, response, and recovery.

The overall flow of the activities is represented using an activity diagram and is shown in Figure 1 based on 15A NCAC 18C .0307(e) of the North Carolina Public Water Systems Rules. Activity diagram can be used to indicate the behavior of the system. Activity modeling emphasizes the inputs, outputs, sequence, and also conditions for coordinating other activities and functions.

Restoration Curves

Earthquake restoration models aid in estimating the economic impacts of earthquakes or similar disasters on life line systems. The restoration process that happens after a damaging event can be represented on a time varying graph denoted as a restoration curve. They usually represent the degree or percentage of lifeline restoration progress after the event. The graphs plotted are generally nonlinear and increase with time. This is true for most of infrastructure systems as the time taken for recovery is large compared to other systems. Restoration curves may differ considerably from one country to other also can differ from one city to another (Oliveira et al. 2006) Restoration curves for water systems were compared in the work by Kameda (2000).

Post Earthquake Investigation

Post earthquake investigation of water systems generally covers pumping stations, treatment facilities, reservoirs, distribution and transmission systems, and fire services (ASCE 1997).Generally for a water system there are control centers and service centers. Control centers monitor the flows, pressures, water levels and the service centers or yards are the places where equipments and materials are stored and also there will be fueling facilities.

The service centers also may dispatch crews that restore the water system. A computer based dispatching system and inventory control may be also located at the center. It will be a location for the personnel to report after a disaster to meet for assignments in the recovery operation. Past performance of the water systems during an earthquake shows that the most physical damage to water systems normally occurs in the pipeline network (ASCE 1997). Therefore, this work focuses on the distribution pipe network of the system.

METHODOLOGY

The methodology adopted in modeling and simulation is straightforward, depicting the real life restoration process. The general flow of the steps that is used in the simulation is given in Figure 2. The initial step of the simulation is the knowledge/acquiring of the damage state. In this paper, the damage state is simulated from the damage probabilities that have been already estimated in a work by Isoyama and Katayama (1981). Once the damage state is simulated or fed into the model the required resources are estimated and compared with available resources at the resource base/ repair yard. If enough resources are available, the restoration starts and goes on concurrently, if not prioritization is done .The timed recovery of the distribution system is monitored and restoration curve is plotted. Data that will change according to location or other factors, for example, the resources available are read from external files during simulation, which enables easier customization for different scenarios. The modeling of the restoration processes is done in different modules, to allow the model to be flexible and changes to be easily made when required. The detailed explanation of the simulation steps is given in the later sections.

Assumptions

Following are the assumptions that has been made when modeling the restoration process

- Emergency supply controls line shut off valves are in operation and is carried out after the event appropriately
- All the nodes function properly
- Main principal components of the systems like reservoirs , tanks are recovered when the restoration of the distribution components is going on
- The repair trucks are loaded with service and repair materials

Network

As an example of a large water distribution system we have taken the trunk water supply network of the old metropolitan Tokyo district. This supply system is capable of providing potable water to some 3,710,000 customers and it can serve a population of around 12,000,000. The distribution area and the schematic diagram is shown in Figure 3

Damage Probability Estimation

Damage state is simulated based on damage probabilities that are estimated for each of the buried trunk lines. (Isoyama and Katayama 1981). The same procedure is adopted to assign the damage probability and is explained briefly in this paper. The basic failure ratio (number of failures per km) for a given earthquake intensity obtained from previous earthquakes was modified based on three factors that influence the damage state of a network: the effect of ground, pipe material and buried depth. The occurrence of failures along the length of the pipeline was assumed to be a Poisson process. The modified failure ratio R_{fm} (number of failures per km) of a pipe section 'i' with a length of L_i is expressed as

$$R_{fm}{}^{i} = C_g{}^{i} x C_p{}^{i} x C_d{}^{i} x R_f \tag{1}$$

where

$C_g{}^{i}$ -Ground Factor

$C_p{}^{i}$ -Pipe Material Factor

$C_d{}^{i}$ -Buried Depth Factor

R_f - Basic failure ratio

Poisson process is assumed along the length of the pipeline, so the probability of failure $P_{kl}{}^{f}$, of the pipeline between nodes k and l is

$$P_f{}^{kl} = 1 - \exp\{-\sum_{i=1}^{n} R_{fm}{}^{i} L_i \tag{2}$$

where n is number of pipe sections between nodes k and l .

The uniform basic failure ratio R_f =0.16 and 0.45 were taken in the area in which the network was laid. R_f =0.16 is the average failure ratio of cast iron pipes caused by the 1923 Kanto earthquake of magnitude 8.3. R_f =0.45 was used as a more critical value. When using the basic failure ratio for a given ratio for a given intensity, the number of failures of cast iron pipe with a buried depth of one to three meter was taken. The ground factor, Cg, was taken as 2.0, 0.9, and 0.4 for different ground conditions. The weighting factors previously obtained by Kubo and Katayama (1975, 1977) for the central part of Tokyo were used. The pipe material factor, Cp, was determined using the damage ratio of water pipes in previous earthquakes. The values of Cp thus obtained are 1.0 for cast iron pipes, 0.2 for ductile cast iron pipes, and 0.1 for arc welded steel pipes. For very old gas welded steel pipes Cp =2.5 was assigned. The buried depth factor, C_d was determined by approximately considering the amplification of seismic motion within a single layered surface ground. The depth factor that was used is given in Table 1.Damage probabilities estimated are given in Table 2.

Damage State Simulation

Based on the damage probabilities estimated, the damaged state of the network was simulated to evaluate the system. Some of the possible damages that can happen to the buried distribution lines are circumferential cracks, compressive buckling at welded slip joints or axial pullout. This model distinguishes pipe damage as leaks and breaks. Damages that result in partial loss of water are categorized as leaks and others as breaks. Distinguishing between breaks and leaks will enable using different repair times and different resource requirements, as repairing leaks require less time and fewer resources.

From a pool of randomly generated numbers, two numbers are selected and it is compared with the damage probabilities estimated. If both the randomly generated numbers are less than the damage probability then it is categorized as a break, if only one of the random numbers is less than the damage probability then the damage state is categorized as a leak If both the random numbers are greater than the damage probability then it is classified as no damage for that simulation. A sample of the output generated is shown in the Figure 4. These can be read form the simulation pages or/and can be written to an external file as desired.

Estimation of Resources Required

The resources, including time required, vary depending on type and extent of damages and also depending on site conditions like buried depth of pipelines. The time that will be taken in general is documented, which will vary depending on the site conditions. For example in the work by Chang et al. (1999), estimates are provided, of the number of the number of leaks and breaks in large and small diameter pipes that could be fixed by one repair worker (as part of a crew) per day. For example, for large diameter pipes (20 inches and larger) , it is assumed that a 4 person crew would require 6 hours to repair a leak or 12 hours to repair a break. In another study based on the Seattle water supply system, unit repair times was estimated specifically that , one repair crew could fix two pipe leaks or one pipe break per 12 hour shift (Ballantyne,1990). A fixed number of crew can be assumed to be available following the disaster or if the data is not available for initial estimation and simulation purposes, a fixed percentage based on the region's population can be assumed. Since repair times for each of the trunk lines in the network were available in our example, it is used in simulation. It is taken that it takes six to seven days for cast iron and ductile iron pipe, 8 to 9 days for a steel pipe and 16 days for a large buried depth. This was used in the simulation, putting a 25 % random variability (longer or lesser) in the documented repair times which can happen due to variable site conditions and other difficulties.

As the damage state was simulated the resources that might be required were estimated. This simulation addressed four resources essential for recovery of water distribution trunk lines during a disaster: restoration crews, repair trucks to take the crew and the materials, excavators and replacement pipes. As this simulation is done for the trunk lines (which are more than 600 mm in diameter) only one size pipe was considered. The model can be modified to include different diameter pipes if a complete distribution network is considered. In this model all the data that could vary frequently were usually read from external files to make the model flexible. For example, the resource that is available at a particular resource base is read from an external file. The simulation can be modified to also account for randomness in the availability of the resources if desired.

Prioritization

An important activity in emergency management for any infrastructure system is the prioritizing the locations. Prioritization rules change depending on the system dealt with and on the operational strategies adopted. While considering the situation after the occurrence of an earthquake, among the various damages to the system, the trunk lines has to be prioritized for resource allocation, since many times the resources available may not meet the requirements. There has been research done in this area to optimize the order of recovery for specified damages, for example work done by Fiedrich et al. (2000). Our paper does not evaluate different prioritization strategies, but use a few prioritization rules to demonstrate the methodology proposed, but can be used for evaluation of different strategies by running different simulations and comparing the results

The prioritization strategy adopted in this simulation is based on the damage state and also based on the importance of the trunk line in the network in terms of its carrying capacity. Among the damage states breaks are given higher priority compared to leaks as the total supply is cut off in case of breaks, and next priority is given to trunk lines having higher branch flow assuming, they serve to higher demand nodes. The branch flow is calculated using Hazen Williams's formula and it is the volume of water that can be conveyed between the adjacent nodes.

Resource Allocation

Managing resource allocation is inevitable in operational contexts, technological contexts, and contemporary technological applications such as production systems, infrastructure systems like transportation systems or water distribution systems. According to Reveliotis (2005), "A common thread running in all of these is that they seek to limit the role of human element to remote high level supervision, while placing the burden of real time monitoring and coordination of the activities upon a computerized control system." Thus managing the resource allocation of a large complex system undoubtedly calls for simulation and modeling before major decisions like the locations of resource hubs are made.

Many previous studies dealt with resource allocation using CPN considered a predetermined sequence for example in projects and processes resource allocation has been attempted using colored Petri nets for project management (Kumar and Ganesh 1998), where in the resources required for each of the processes is mostly known a priori. Resource allocation to infrastructure systems for disaster management is different from the projects / processes because of the following reasons

- Occurrence of disaster, locations, and components of the system that might get affected is uncertain
- Resource allocation has to dynamic as the rate of damage and in turn the resources required is not known in advance
- Once the disaster happen the factor time is very important particularly in the case of lifeline infrastructures.
- Work can be interrupted between stages as there is no fixed flow, but it is mostly priorities whereas in processes fixed flow must be adhered to.

Once the location priority is known, the available resources must be allocated according to availability. In this paper, it is assumed that the damage data at various locations come directly from the field or be estimated indirectly using advanced technologies such as remote sensing data if the scenario is a real time event. If the restoration modeling is done for pre disaster planning, the damage state can be simulated as explained in this paper or using some other prediction tools like Artificial Neural Networks as in the research done by Luna et al (2007).

Resources are allocated based on the priority calculated for the simulated damage state of the system. The system we consider here has two resource bases with different storage levels. Based on the proximity the damaged trunk lines to the resource bases resources are drawn. If any of the resources are depleted, the simulation proceeds, drawing the additional resources required. Since planning managers like to know from simulation what stage of the restoration process were the resources got depleted and the corresponding time, monitoring tool is applied at this part of the simulation which records the step and time of occurrence of that activity. In other words whenever any of the required resources fall below a certain predetermined level it automatically draws the required resources and completes the simulation, but writes into the monitoring file what time and stage of the restoration that happened. But if it is desired by the planning personnel to monitor during the simulation then a break point monitor can be established in which the simulation stops when the required resources go below a certain level. The simulation updates the available resources depending on whether the resources are reusable like manpower, service vehicles, or whether it is consumable resources like pipes, valves etc.

Loss of Function and Restoration time

As mentioned earlier in the paper, due to the physical damage which is the hard damage there will loss of intended functions which is termed as soft damage. The factors causing soft damage or the loss of function and the restoration time has been mentioned in the ATC-13(1985). The degree of damage at a particular facility and degree of damage to all lifelines on which the facility is dependent are the prime factors. The specific factors that affect loss of function are

- Direct damage to the facility (structural and non structural)
- Equipment damage at the facility (contents)
- Damage to service lifelines at the facility
- Personnel loss
- Damage to remote lifelines serving the facility
- Interruption to raw material supplies , replacement parts and services to the facility

The first four items can be regarded as local or on site factors, while last two, represent affects external to the facility.

In our research we focus on the last two factors which require a global system analysis for evaluation (ATC, 1985). The restoration time depends on

- Degree of damage
- Importance of the facility in post earthquake recovery
- The availability of manpower and resources (construction material and equipment)
- The availability of supplies, replacement parts, and services.

Because of the paucity of the statistical data loss of function and restoration time was estimated in earlier earthquakes before 1985 by soliciting expert opinions through questionnaires. (ATC 1985). In this work the loss of function is estimated based on the loss of carrying capacity of the system assuming both are related. Based on the damage state simulated and the branch flow of the trunk lines the loss of carrying capacity of the system is estimated. Since the damage states are categorized as breaks and leaks, it is assumed that the complete carrying capacity is lost for the trunk lines where the breaks have occurred. For the leaks it is assumed fifty percent of the carrying capacity is lost. Extract from the simulation page where this is done is shown in Figure5. Variable capacity loss for leaks can be incorporated also if desired.

Timed Recovery

The simulation gives time history of the restoration process as output. Even though the simulation is done for distribution network of the system it can be similarly modeled for other system components also. In the event of disruption of system due to earthquake it is assumed the time for which the damage is occurring is comparatively negligible compared with time that is taken for restoration. So the restoration curve will be continuously progressing, the slope indicating the restoration progress

In this simulation time taken to repair breaks has not been given much variability, but for the leaks time taken for recovery is given a higher variability as the category of leaks can vary from just the disjointing of the pipes to higher order leaks, the degree which is usually represented by the ratio of crack to the circumference of the pipe. The simulation stops when the full recovery of the system has occurred. Because randomness is incorporated into the simulation the results vary, running it an enough number of times help it converge and get an average restoration curve

RESULTS

Figure 6 show the restoration curves generated for multiple simulations for damage probability assigned to the network. A curve encompassing the restoration curves obtained for 100 simulations is shown as the shaded area. The restoration curves obtained closely follows the average restoration curve obtained by Isoyama and Katayama (1981) for the same dataset which is shown in Figure 6 with square marked curve. The upper boundary of shaded area represent the best case scenario, the system can be expected to get recovered the earliest, as represented by this curve. This is plotted by highest percentage of restoration that is achieved on each of the days after the damaging disaster. Similarly the worst case scenario represents the lowest percentage of recovery that is possible to achieve for the particular trunk network. The curve plotted with the triangles representing the particular curve is an example case from one of the random simulations, in which 80% percent of the recovery is achieved in 8 days. Between the days 10 and 15 the rate of recovery is low indicating only lower capacity are getting recovered during that period and restoration of some higher capacity lines getting recovered after day 16 which is pointed by the higher slope of the curve.

DISCUSSION

The proposed methodology and simulation can be used for real time or hypothetical earthquakes. The restoration process modeled has mostly modular structure in which data components and parameters of the system can be updated or replaced. This can be better customized for different locations and facilities by varying the input files. This modeling and simulation can give valuable insights into the restoration process and into improvements that must be made, particularly in areas where earthquakes have not previously occurred, but are possible. The expected effectiveness of different mitigation strategies can be evaluated using the simulation. When using colored Petri nets the system is formally verifiable Restoration modeling approach helps to study the geographic variability of the risk and the adequacy of the post earthquake recovery preparedness.

Other than the methodology adopted here for the simulation of the damage state, other methods like estimating the damage state using prediction tools can also be used. Though the pipes are fixed individually, their priority is set based on their role in the network capacity-wise. While adopting the prioritization in this simulation emphasis is placed on the physical recovery of the system than on the node connectivity. Analyzing system performance by only considering connectivity will be not always be realistic because even if there is a transmission path between the supply and demand node does not always guarantee that water reaches a particular node unless there is enough branch flow

When the simulation is extended to the whole distribution system, detailed damage probability may not be available. In distribution systems damage is usually specified by the number of breaks or leaks per kilometer, which is more apt for use in simulations when considering whole network. When simulation is used for resource allocation in a real scenario, the simulation of the damage state will be bypassed and use the damage data file directly.

CONCLUSIONS

A simulation based methodology is developed for modeling the restoration process for a water distribution system. This methodology can aid decision makers who are dealing with large systems in complex scenarios. This simulation based restoration modeling approach overcomes some of the limitations of past work and enables realistic modeling of the restoration process. Disaster management can be made more simplified and much more efficient with the resource allocation being simulated. It helps to decide on the optimum amount of resources in each resource hub and also while planning mutual aid agreements. This methodology can be used for similar events and similar infrastructures even when requirements and resource availability changes. It is envisioned that this simulation can be used in conjunction with other pre event and post event loss reduction strategies and also to architect reliable and resilient water distribution system.

The findings are that (1) Discrete event simulation proves to better method as there are no unrealistic simplifying assumptions. (2) Compared to other simulation methods, each possible state achieved by the system can be monitored and analyzed. This property of colored Petri nets makes it different from and efficient compared to other simulation methods. (3) The resource limiting the progress of the restoration activity and the time in which it can possibly happen can be readily visualized and monitored (4) The effect of changes in prioritization rules, the effect of resources stored and effect of mutual aid agreements on restoration time can be analyzed and thus can serve a good decision support system. The associated uncertainties can be mathematically modeled and modified for different conditions. (5) As the model is simulated mainly by reading external files it can be easily customized for different systems by changing the input files

This simulation can potentially be useful in a number of additional ways. Simulation models can help assess whether restoration strategies are good enough for a particular magnitude earthquake. Comparing the different restoration time emergency management plans can be tailored for each location. It can give an indication of what is the earliest possible recovery time that can be expected for a particular magnitude earthquake and particular location. So the proposed methodology can be used by planning engineers and decision makers to better serve the community.

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Table 1. Values of Cd (Isoyama and Katayama 1981)

Buried Depth			**Cd**
Less than 5 m			1
Greater than 5 m	Diluvial Layer	Cg=0.4	0.4
		Cg=0.9	0.44
		Cg= 2.0	0.2
	Alluvial Layer	0<=Z<0.3	1
		0.3<=Z<0.6	0.7
		0.6<=Z<1.0	0.4

Z= (Buried depth/depth of Alluvial layer)

Table 2. Damage Probabilities of Trunk lines

Link No	**Damage probability**	
	R_f=0.16	R_f=0.45
1	0.042	0.115
2	0.029	0.079
3	0.015	0.4
4	0.216	0.495
5	0.01	0.034
6	0.507	0.863
7	0.119	0.299
8	0.003	0.007
9	0.068	0.179
10	0.068	0.181
11	0.766	0.994
12	0.007	0.019
13	0.033	0.13
14	0.117	0.296
15	0.134	0.333
16	0.284	0.61
17	0.004	0.011
18	0.198	0.463
19	0.027	0.075
20	0.179	0.426
21	0.068	0.18
22	0.064	0.17
23	0.176	0.419
24	0.277	0.598
25	0.014	0.04
26	0.078	0.204
27	0.025	0.07

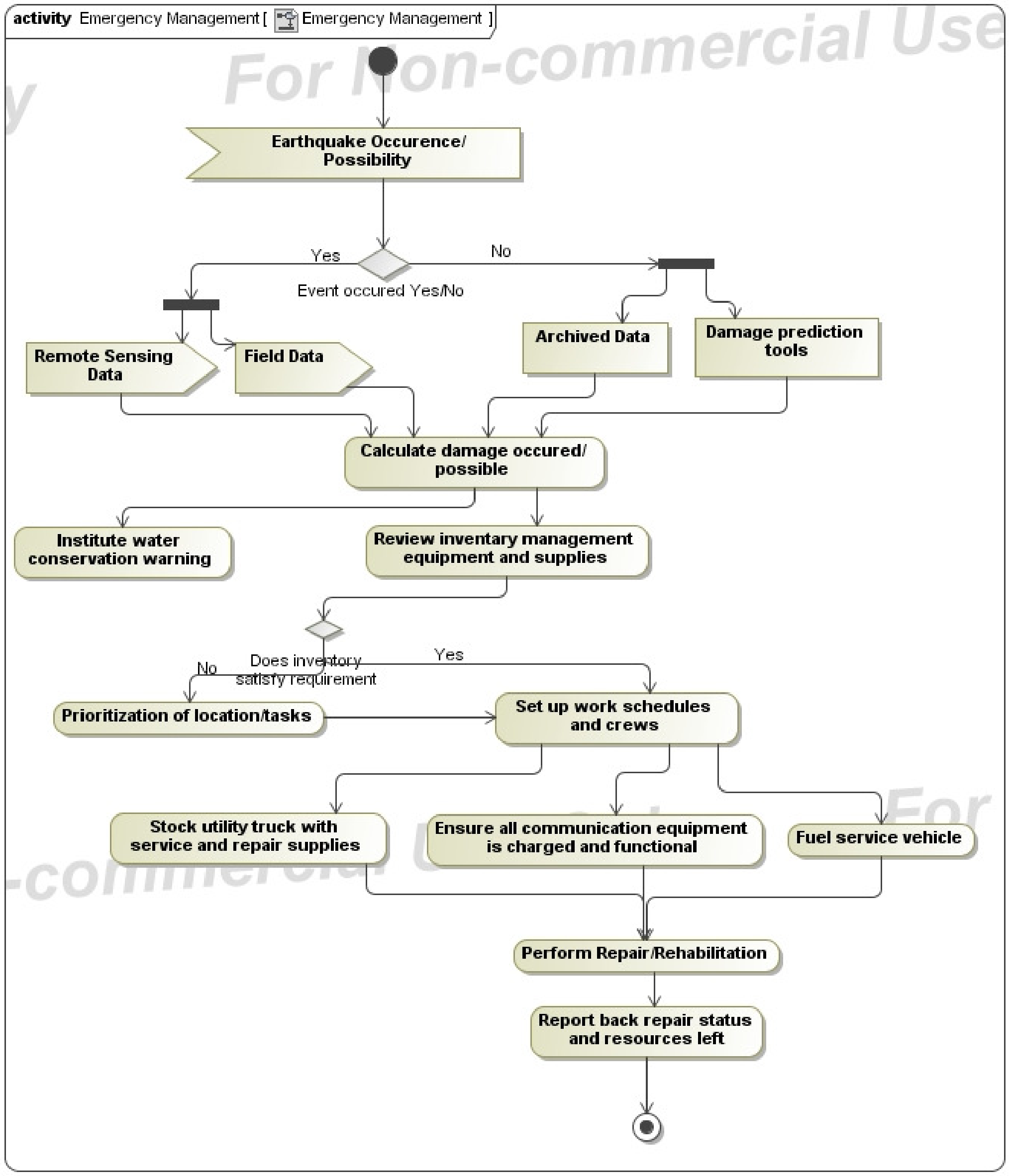

FIG. 1. Emergency Management Activity Diagram

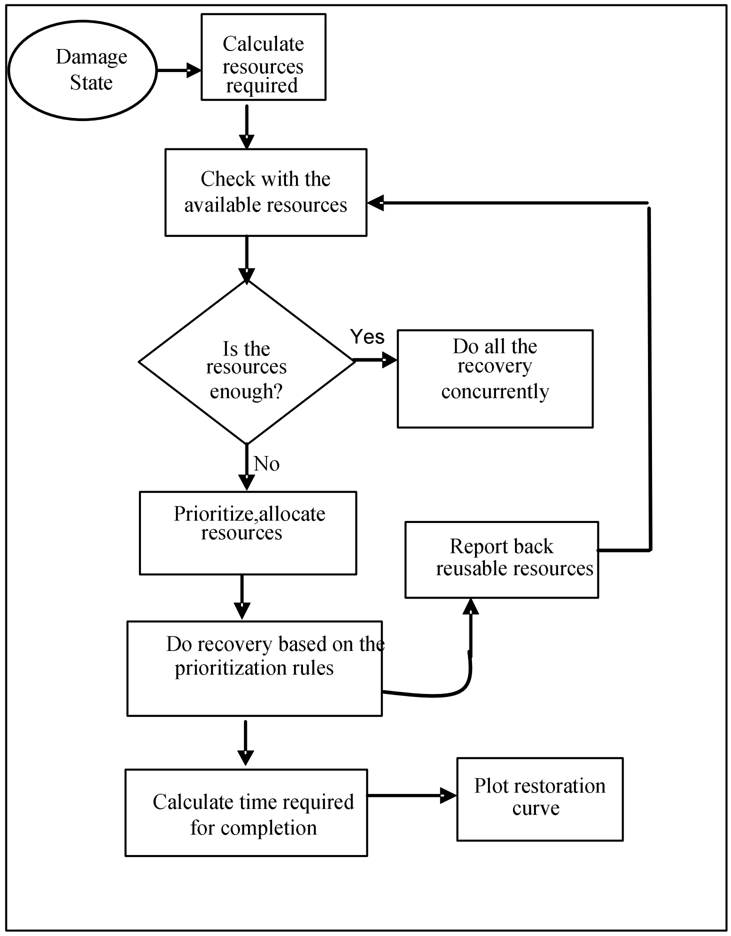

FIG. 2. Flow chart of Simulation steps

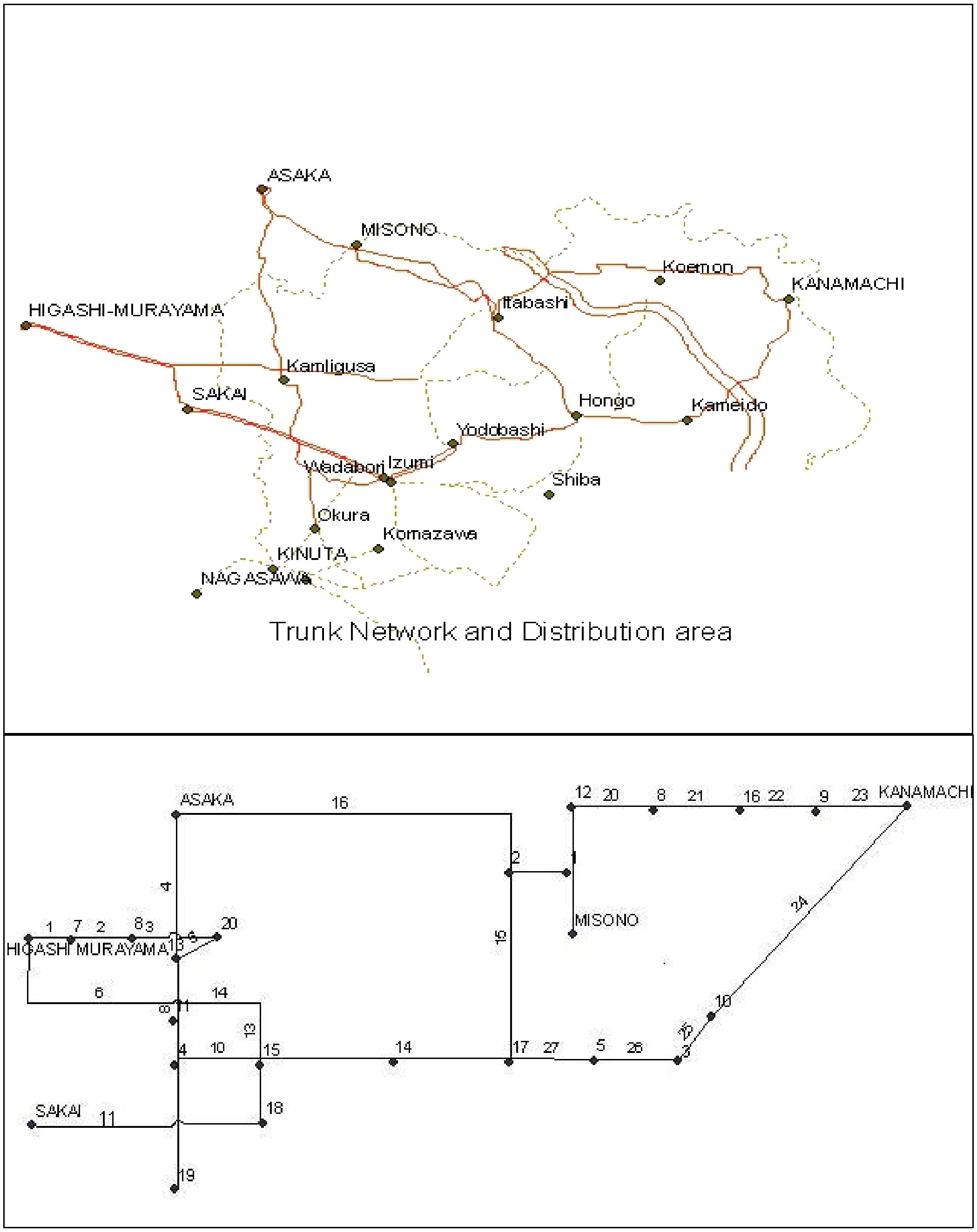

FIG. 3. Distribution Area and Schematic Representation of the Trunk Network (Isoyama and Katayama 1981)

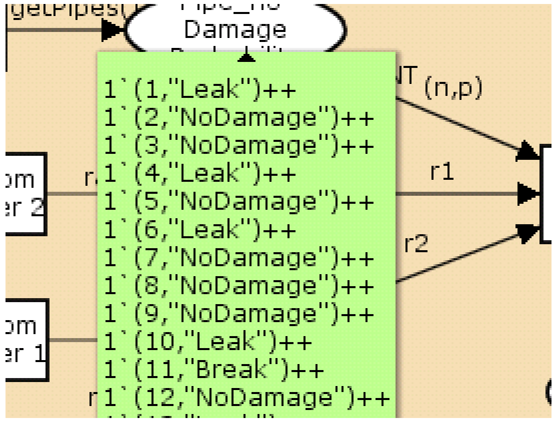

FIG. 4. Sample Simulation Output of the Damage State

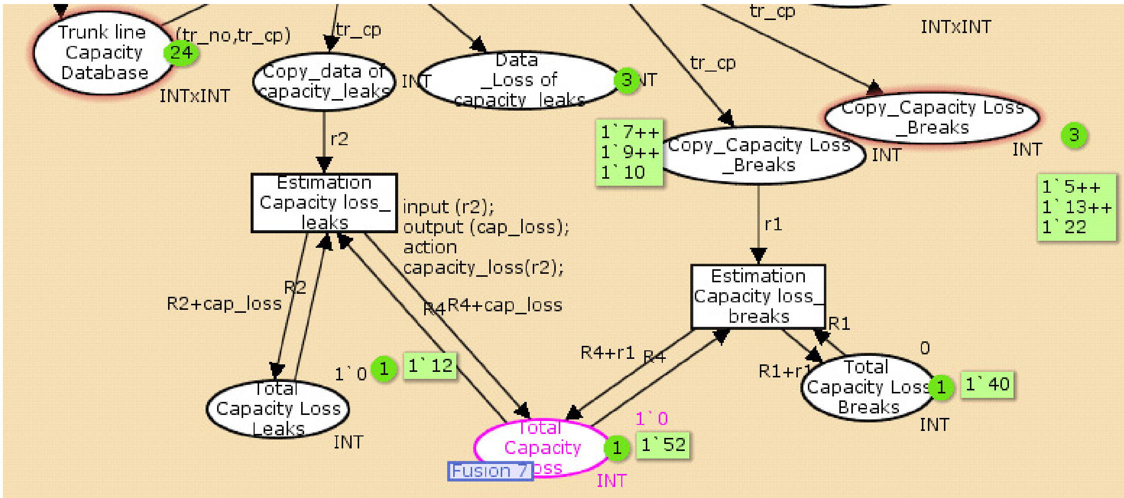

FIG. 5. Extract from Module where Total Capacity Loss of the System is Estimated

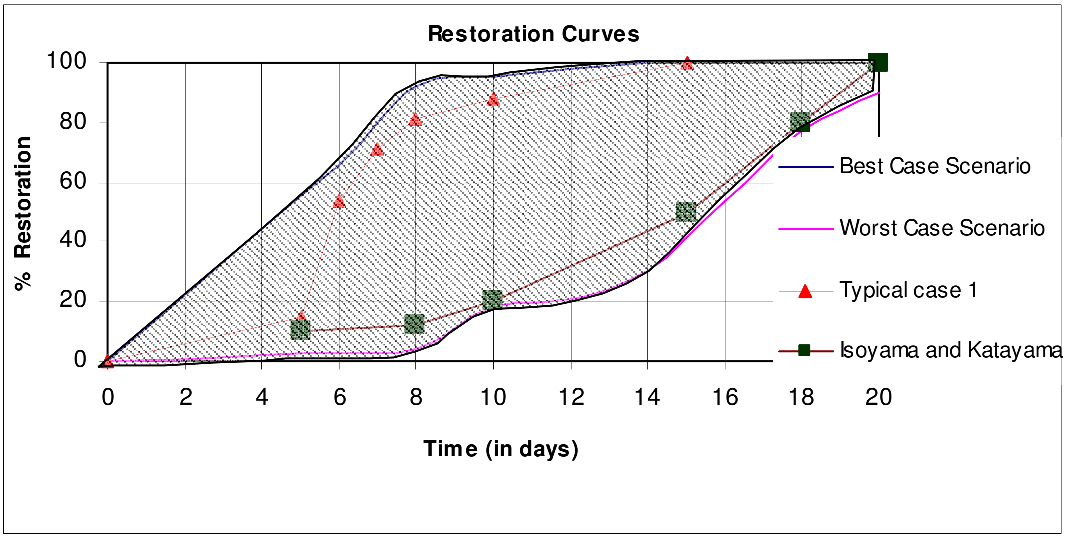

FIG. 6. Restoration Curves plotted for 100 simulations

2. OVERALL DISCUSSION AND FUTURE WORK

This research focused on the distribution network of the water system as it is the most vulnerable part of the water system for the earthquake damage scenario considered. But for the overall system analysis the other components of the system like the water tanks, reservoirs, pumping stations can be incorporated. In a study by American Lifeline Alliance (ALA) (Eguchi and Honegger 2002) the vulnerability of major system components, several damage states and the failure mechanisms that can lead to these damage states is estimated using a fault tree method. For example, one of the damage states is the functionality loss of the anchored steel water tank. Resources that are required for the damage state of the water tank can be estimated for various failure mechanisms such as damage to inlet pipes, uplifting of tank walls or elephant foot buckling. Similar to damage states described for the water tank, pipe leaks and breaks is considered in this thesis for the distribution system. Categorizing the various failure possibilities into a number of damage states and estimating the time for the repair of the failures, and calculating the damage probability and incorporating these system components into the already developed simulation methodologies will give a more complete picture of the performance of the system.

In a study by the Applied Technology Council (ATC) (ATC, 1985), the restoration curves developed are for the damage estimates of average California construction. Seismic resistant design and practices have clearly improved over the last 40-50 years, so, it is useful to have a model that can be modified according to the changes, that is feasible with methodology proposed and is convenient with the modular approach used in this thesis. The model is not designed specifically for a particular water system, but is modeled such that the input files can be changed depending on specific system. This makes the model different from a few discrete event simulations that have been tried before post earthquake restoration modeling. The model is flexible and is represented graphically; any modifications can be implemented easily using the GUI tools. The modeling of the restoration process as modules helps to implement changes and customize which can effectively represent different systems and run the simulations

Scalar measures the water system's rapidity in the form of probability of restoring a specified number of customers in specified amount of time similar to Multidisciplinary Center for Earthquake Engineering Research (MCEER) researchers has proposed for the electric power systems. The simulation can be extended by incorporating fragility curves developed for different system components if available. Fragility curves depict the relationship between elements failure probability and the force or action assigned. The use of fragility curves is an effective way to characterize the probabilistic nature of the physical phenomena, which reflects the uncertainty and randomness.

3. CLOSING REMARKS

The computational methods used can aid in the evaluation of a water distribution system performance during a natural disasters like an earthquake. The demonstrated methodologies can aid decision makers in planning earthquake resilient water systems. Disaster management can be simplified by the resource allocation being simulated .The graphical modeling helps to visualize better compared to other methods so far and thus gives a clearer picture. This methodology can be extended for similar events and similar infrastructures. The results can be used as a means of estimating the direct and indirect economic losses caused by disruption of a water system. Further, the impact of earthquake induced water disruption on people’s day to day activities can be reduced.

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APPENDIX A.

PIPE DAMAGE/REPAIR DATA

(Source: American Lifeline Alliance 2001)

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1020	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.099	---	PGA = 0.211	---	Included in 1001 to 1010
1021	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.288	---	PGA = 0.306	---	Included in 1001 to 1010
1022	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.252	---	PGA = 0.478	---	Included in 1001 to 1010
1023	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.171	---	PGA = 0.572	---	Included in 1001 to 1010
1024	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.585	---	PGA = 0.595	---	Included in 1001 to 1010
1025	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.441	---	PGA = 0.677	---	Included in 1001 to 1010
1026	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.099	---	PGA = 0.710	---	Included in 1001 to 1010
1027	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	1.098	---	PGA = 0.792	---	Included in 1001 to 1010
1028	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	1.458	---	PGA = 0.819	---	Included in 1001 to 1010
1029	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.189	---	PGA = 0.834	---	Included in 1001 to 1010
1030	1994 Northridge	6.7	DI	DS	16.1	2	0.0236	0.0253	PGV = 47.2	47.2	1.07xRate (see Note 7)
1031	1994 Northridge	6.7	DI	DS	14.4	1	0.0131	0.014	PGV = 35.8	35.8	1.07xRate (see Note 7)
1032	1994 Northridge	6.7	DI	DS	13.4	2	0.0283	0.0303	PGV = 29.3	29.3	1.07xRate (see Note 7)
1033	1994 Northridge	6.7	DI	DS	12.8	6	0.0887	0.0949	PGV = 22.8	22.8	1.07xRate (see Note 7)
1034	1994 Northridge	6.7	DI	DS	11.3	1	0.0167	0.0179	PGV = 17.9	17.9	1.07xRate (see Note 7)
1035	1994 Northridge	6.7	DI	DS	20.1	3	0.0282	0.0302	PGV = 14.6	14.6	1.07xRate (see Note 7)
1036	1994 Northridge	6.7	DI	DS	25.2	2	0.015	0.0161	PGV = 11.4	11.4	1.07xRate (see Note 7)
1037	1994 Northridge	6.7	DI	DS	57.9	6	0.0196	0.021	PGV = 8.1	8.1	1.07xRate (see Note 7)
1038	1994 Northridge	6.7	DI	DS	72.9	1	0.0026	0.002	PGV = 4.9	4	Combine w/ 1039, 1.07xRate
1039	1994 Northridge	6.7	DI	DS	26.4	0	0	---	PGV = 1.6	---	

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1040	1994 Northridge	6.7	AC	DS	15.8	0	0	---	PGV = 35.8	---	
1041	1994 Northridge	6.7	AC	DS	13.4	0	0	---	PGV = 29.3	---	
1042	1994 Northridge	6.7	AC	DS	15.2	7	0.0873	0.0216	PGV = 21.1	25.3	Combine w/ 1040, 1041, 1043, 1.07xRate
1043	1994 Northridge	6.7	AC	DS	21.3	0	0	---	PGV = 17.9	---	
1044	1994 Northridge	6.7	AC	DS	23.6	0	0	---	PGV = 14.6	---	
1045	1994 Northridge	6.7	AC	DS	73.6	2	0.0051	0.0042	PGV = 11.4	12.2	Combine w/ 1044, 1.07xRate
1046	1994 Northridge	6.7	AC	DS	147.2	15	0.0193	0.0207	PGV = 8.1	8.1	
1047	1994 Northridge	6.7	AC	DS	192.4	2	0.002	0.0014	PGV = 4.9	3.8	Combine w/ 1048, 1.07xRate
1048	1994 Northridge	6.7	AC	DS	98.3	0	0	---	PGV = 1.6	---	
1049	1994 Northridge	6.7	CI	DS	78.9	60	0.1441	0.1541	PGV = 52.1	52.1	1.07xRate
1050	1994 Northridge	6.7	CI	DS	84.8	11	0.0246	0.0263	PGV = 45.6	45.6	1.07xRate
1051	1994 Northridge	6.7	CI	DS	101.8	11	0.0205	0.0219	PGV = 39.0	39	1.07xRate
1052	1994 Northridge	6.7	CI	DS	117.6	4	0.0064	0.0068	PGV = 32.5	32.5	1.07xRate
1053	1994 Northridge	6.7	CI	DS	87.6	24	0.054	0.0578	PGV = 27.7	27.7	1.07xRate
1054	1994 Northridge	6.7	CI	DS	111.7	39	0.0662	0.0708	PGV = 24.4	24.4	1.07xRate
1055	1994 Northridge	6.7	CI	DS	222.7	87	0.0739	0.079	PGV = 21.1	21.1	1.07xRate
1056	1994 Northridge	6.7	CI	DS	313.9	56	0.0337	0.0362	PGV = 17.9	17.9	1.07xRate
1057	1994 Northridge	6.7	CI	DS	503.1	59	0.0221	0.0236	PGV = 14.6	14.6	1.07xRate
1058	1994 Northridge	6.7	CI	DS	699.7	111	0.03	0.0321	PGV = 11.4	11.4	1.07xRate
1059	1994 Northridge	6.7	CI	DS	1370.7	166	0.023	0.0246	PGV = 8.1	8.1	1.07xRate

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1060	1994 Northridge	6.7	CI	DS	1055.8	44	0.0079	0.0073	PGV = 4.9	4.5	Combine w/ 1061, 1.07xRate
1061	1994 Northridge	6.7	CI	DS	156.8	0	0	---	PGV = 1.6	---	
1062	1994 Northridge	6.7	CP	LG	NR	NR	0.102	0.102	PGV = 50.7	42.3	0.83xPGV (see Note 8)
1063	1994 Northridge	6.7	S	LG	NR	NR	0.0839	0.0839	PGV = 54.3	45.3	0.83xPGV (see Note 8)
1064	1994 Northridge	6.7	S	LG	NR	NR	0.0396	0.0396	PGV = 33.2	27.7	0.83xPGV (see Note 8)
1065	1994 Northridge	6.7	S	LG	NR	NR	0.0092	0.0092	PGV = 19.8	16.5	0.83xPGV (see Note 8)
1066	1994 Northridge	6.7	S	LG	NR	NR	0.0031	0.0031	PGV = 13.7	11.4	0.83xPGV (see Note 8)
1067	1994 Northridge	6.7	S	LG	NR	NR	0.0031	0.0031	PGV = 9.7	8.1	0.83xPGV (see Note 8)
1068	1994 Northridge	6.7	AC	DS	NR	NR	0.0183	---	PGV = 9.8	---	Already in ALA data above
1069	1994 Northridge	6.7	AC	DS	NR	NR	0.0031	---	PGV = 5.9	---	Already in ALA data above
1070	1994 Northridge	6.7	DI	DS	NR	NR	0.0122	---	PGV = 12.5	---	Already in ALA data above
1071	1994 Northridge	6.7	S	DS	NR	NR	0.0854	0.0914	PGV = 21.5	17.9	1.07xRate, 0.83xPGV
1072	1994 Northridge	6.7	S	DS	NR	NR	0.0488	0.0522	PGV = 13.8	11.5	1.07xRate, 0.83xPGV
1073	1994 Northridge	6.7	S	DS	NR	NR	0.0549	0.0587	PGV = 9.9	8.3	1.07xRate, 0.83xPGV
1074	1994 Northridge	6.7	S	DS	NR	NR	0.0515	0.0551	PGV = 5.9	4.9	1.07xRate, 0.83xPGV
1075	1994 Northridge	6.7	CI	DS	NR	NR	0.0674	---	PGV = 29.4	---	Already in ALA data above
1076	1994 Northridge	6.7	CI	DS	NR	NR	0.0759	---	PGV = 25.7	---	Already in ALA data above
1077	1994 Northridge	6.7	CI	DS	NR	NR	0.0338	---	PGV = 21.8	---	Already in ALA data above
1078	1994 Northridge	6.7	CI	DS	NR	NR	0.0213	---	PGV = 17.8	---	Already in ALA data above
1079	1994 Northridge	6.7	CI	DS	NR	NR	0.0031	---	PGV = 13.7	---	Already in ALA data above

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1080	1994 Northridge	6.7	CI	DS	NR	NR	0.0241	---	PGV = 9.8	---	Already in ALA data above
1081	1994 Northridge	6.7	CI	DS	NR	NR	0.0061	---	PGV = 5.9	---	Already in ALA data above
1082	1989 Loma Prieta	6.9	S	DS	60	47	0.148	0.148	PGV = 17.0	17	Supersedes 1094 to 1096
1083	1989 Loma Prieta	6.9	S	DS	279	9	0.0061	0.0061	PGV = 7.0	7	Supersedes 1094 to 1096
1084	1989 Loma Prieta	6.9	S	DS	45	2	0.0084	0.0084	PGV = 5.0	5	Supersedes 1094 to 1096
1085	1989 Loma Prieta	6.9	S	DS	374	5	0.0025	0.0025	PGV = 3.0	3	Supersedes 1094 to 1096
1086	1989 Loma Prieta	6.9	AC	SM	46.2	3	0.0123	0.0123	PGV = 17.0	17	Supersedes 1097 to 1099
1087	1989 Loma Prieta	6.9	AC	SM	438	2	0.0009	0.0009	PGV = 7.0	7	Supersedes 1097 to 1099
1088	1989 Loma Prieta	6.9	AC	SM	79.5	1	0.0024	0.0024	PGV = 5.0	5	Supersedes 1097 to 1099
1089	1989 Loma Prieta	6.9	AC	SM	445	8	0.0034	0.0034	PGV = 3.0	3	Supersedes 1097 to 1099
1090	1989 Loma Prieta	6.9	CI	DS	20.6	10	0.0919	0.0919	PGV = 17.0	17	Supersedes 1100 to 1102
1091	1989 Loma Prieta	6.9	CI	DS	879	24	0.0052	0.0052	PGV = 7.0	7	Supersedes 1100 to 1102
1092	1989 Loma Prieta	6.9	CI	DS	123	8	0.0123	0.0123	PGV = 5.0	5	Supersedes 1100 to 1102
1093	1989 Loma Prieta	6.9	CI	DS	473	14	0.0056	0.0056	PGV = 3.0	3	Supersedes 1100 to 1102
1094	1989 Loma Prieta	6.9	S	DS	NR	NR	0.097	---	PGV = 16.0	---	
1095	1989 Loma Prieta	6.9	S	DS	NR	NR	0.0052	---	PGV = 7.0	---	
1096	1989 Loma Prieta	6.9	S	DS	NR	NR	0.0031	---	PGV = 2.5	---	
1097	1989 Loma Prieta	6.9	AC	DS	NR	NR	0.0122	---	PGV = 16.0	---	
1098	1989 Loma Prieta	6.9	AC	DS	NR	NR	0.0012	---	PGV = 7.0	---	
1099	1989 Loma Prieta	6.9	AC	DS	NR	NR	0.0031	---	PGV = 2.5	---	

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1100	1989 Loma Prieta	6.9	CI	DS	NR	NR	0.079	---	PGV = 16.0	---	
1101	1989 Loma Prieta	6.9	CI	DS	NR	NR	0.0055	---	PGV = 7.0	---	
1102	1989 Loma Prieta	6.9	CI	DS	NR	NR	0.0061	---	PGV = 2.5	---	
1103	1989 Mexico	7.4	CP	LG	NR	NR	0.0518	0.0518	PGV = 9.8	9.8	
1104	1989 Loma Prieta	6.9	CI	DS	1080	15	0.0026	0.0026	PGV = 5.3	5.3	
1105	1987 Whittier	5.9&5.3	CI	DS	110	14	0.0241	---	PGV = 11.0	---	Main and aftershock magnitudes (Note 10)
1106	1985 Mexico City	8.1&7.5	CP	LG	NR	NR	0.457	---	PGV = 21.3	---	Main and aftershock magnitudes (Note 10)
1107	1985 Mexico City	8.1&7.5	MX	LG	NR	NR	0.0031	---	PGV = 4.3	---	Main and aftershock magnitudes (Note 10)
1108	1985 Mexico City	8.1&7.5	MX	LG	NR	NR	0.0213	---	PGV = 4.7	---	Main and aftershock magnitudes (Note 10)
1109	1985 Mexico City	8.1&7.5	MX	LG	NR	NR	0.137	---	PGV = 18.9	---	Main and aftershock magnitudes (Note 10)
1110	1983 Coalinga	6.7	AC	SM	NR	NR	0.101	0.101	PGV = 11.8	11.8	
1111	1983 Coalinga	6.7	CI	SM	NR	NR	0.24	---	PGV = 11.8	---	Corrosion bias
1112	1979 Imperial Val.	6.5	AC	DS	NR	NR	0.0183	0.0183	PGV = 23.7	23.7	
1113	1979 Imperial Val.	6.5	CI	DS	11.5	19	0.314	---	MMI = 7	---	Corrosion bias
1114	1972 Managua	6.3	AC	SM	205	393	0.363	---	PGA = 0.41	---	See Note 9
1115	1972 Managua	6.3	CI	LG	18.8	11	0.11	---	PGA = 0.41	---	See Note 9
1116	1972 Managua	6.3	CI	SM	55.8	107	0.363	---	PGA = 0.41	---	See Note 9
1117	1971 San Fernando	6.7	CI	SM	52.7	3	0.0122	0.0122	PGA = 0.27	13.8	PGV (c/s)=130xPGA per Wald Figs. 1&2
1118	1971 San Fernando	6.7	CI	SM	60	5	0.0152	0.0152	PGA = 0.28	14.3	PGV (c/s)=130xPGA per Wald Figs. 1&2

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1119	1971 San Fernando	6.7	CI	SM	52.2	7	0.0244	0.0244	PGA = 0.29	14.8	PGV (c/s)=130xPGA per Wald Figs. 1&2
1120	1971 San Fernando	6.7	CI	SM	48.8	5	0.0183	0.0183	PGA = 0.29	14.8	PGV (c/s)=130xPGA per Wald Figs. 1&2
1121	1971 San Fernando	6.7	CI	SM	49.1	6	0.0244	0.0244	PGA = 0.30	15.4	PGV (c/s)=130xPGA per Wald Figs. 1&2
1122	1971 San Fernando	6.7	CI	SM	50.6	9	0.0335	0.0335	PGA = 0.31	15.9	PGV (c/s)=130xPGA per Wald Figs. 1&2
1123	1971 San Fernando	6.7	CI	SM	59.8	19	0.061	0.061	PGA = 0.32	16.4	PGV (c/s)=130xPGA per Wald Figs. 1&2
1124	1971 San Fernando	6.7	CI	SM	40.1	26	0.122	0.122	PGA = 0.33	16.9	PGV (c/s)=130xPGA per Wald Figs. 1&2
1125	1971 San Fernando	6.7	CI	SM	31.9	22	0.131	0.131	PGA = 0.34	17.4	PGV (c/s)=130xPGA per Wald Figs. 1&2
1126	1971 San Fernando	6.7	CI	SM	18.6	24	0.244	--	PGA = 0.35	--	See Note 9
1127	1971 San Fernando	6.7	CI	SM	16.1	16	0.189	--	PGA = 0.36	--	See Note 9
1128	1971 San Fernando	6.7	CI	SM	19.6	26	0.253	--	PGA = 0.38	--	See Note 9
1129	1971 San Fernando	6.7	CI	SM	20.6	77	0.707	--	PGA = 0.39	--	See Note 9
1130	1971 San Fernando	6.7	CI	SM	21.8	35	0.305	--	PGA = 0.41	--	See Note 9
1131	1971 San Fernando	6.7	CI	SM	16.8	43	0.482	--	PGA = 0.42	--	See Note 9
1132	1971 San Fernando	6.7	CI	SM	15	53	0.668	--	PGA = 0.44	--	See Note 9
1133	1971 San Fernando	6.7	CI	SM	17.8	53	0.564	--	PGA = 0.46	--	See Note 9
1134	1971 San Fernando	6.7	CI	SM	19.3	53	0.521	--	PGA = 0.48	--	See Note 9
1135	1971 San Fernando	6.7	CI	SM	9.1	24	0.5	--	PGA = 0.50	--	See Note 9
1136	1971 San Fernando	6.7	CI	DS	333	84	0.0488	0.0488	MMI = 8	26	PGV per Wald el al, 1999 Fig. 2
1137	1971 San Fernando	6.7	CI	DS	3540	55	0.0029	0.0029	MMI = 7	9.1	PGV per Wald el al, 1999 Fig. 2
1138	1971 San Fernando	6.7	CI	SM	NR	NR	0.0073	--	PGV =	--	Same data set as 1140 and 1141

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
									5.9		
1139	1971 San Fernando	6.7	CI	SM	NR	NR	0.0473	---	PGV = 11.8	---	Same data set as 1140 and 1141
1140	1971 San Fernando	6.7	CI	DS	169	6	0.0067	0.0067	PGV = 7.1	7.1	
1141	1971 San Fernando	6.7	CI	DS	151	10	0.0125	0.0125	PGV = 11.8	11.8	
1142	1969 Santa Rosa	5.6&5.7	CI	DS	136	7	0.0098	---	MMI = 7	---	Main and aftershock magnitudes (Note 10)
1143	1969 Santa Rosa	5.6&5.7	CI	SM	NR	NR	0.0085	---	PGV = 5.9	---	Main and aftershock magnitudes (Note 10)
1144	1968 Tokachi-oki	7.9	AC	DS	24.8	77	0.589	---	MMI = 6 - 7	---	See Note 9
1145	1968 Tokachi-oki	7.9	MX	DS	83.9	22	0.0488	---	MMI = 6 - 7	---	See Note 9
1146	1968 Tokachi-oki	7.9	MX	DS	98.1	16	0.0305	---	MMI = 7 - 8	---	See Note 9
1147	1968 Tokachi-oki	7.9	MX	DS	101	16	0.0305	---	MMI = 6 - 7	---	See Note 9
1148	1968 Tokachi-oki	7.9	MX	DS	150	116	0.146	---	MMI = 7 - 8	---	See Note 9
1149	1968 Tokachi-oki	7.9	AC	DS	13.7	58	0.805	---	MMI = 7 - 8	---	See Note 9
1150	1968 Tokachi-oki	7.9	CI	DS	5.6	7	0.238	---	MMI = 7 - 8	---	See Note 9
1151	1968 Tokachi-oki	7.9	MX	DS	33.5	46	0.259	---	MMI = 7 - 8	---	See Note 9
1152	1968 Tokachi-oki	7.9	AC	DS	31.1	13	0.0793	---	MMI = 7 - 8	---	See Note 9
1153	1968 Tokachi-oki	7.9	CI	DS	13.7	29	0.403	---	MMI = 7 - 8	---	See Note 9
1154	1968 Tokachi-oki	7.9	MX	DS	60.9	81	0.369	---	MMI = 7 - 8	---	See Note 9
1155	1965 Puget Sound	6.5	CI	DS	69.7	13	0.0366	0.0366	MMI = 8	16.7	PGV per Wald el al, 1999 eqn 2
1156	1965 Puget Sound	6.5	CI	DS	1180	14	0.0022	0.0022	MMI = 7	8.6	PGV per Wald el al, 1999 eqn 2
1157	1965 Puget Sound	6.5	CI	SM	NR	NR	0.0021	---	PGV = 3.0	---	Data included in 1155 and 1156
1158	1964 Niigata	7.5	CI	SM	293	215	0.14	0.14	PGA = 0.16	6	PGV (c/s)=95xPGA per Wald Figs. 3&4

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1159	1949 Puget Sound	7.1	CI	DS	52.2	24	0.0884	0.0884	MMI = 8	16.7	PGV per Wald el al, 1999 eqn 2
1160	1949 Puget Sound	7.1	CI	DS	819	17	0.004	0.004	MMI = 7	8.6	PGV per Wald el al, 1999 eqn 2
1161	1948 Fukui	7.3	CI	DS	49.7	150	0.579	---	PGA = 0.51	---	See Note 9
1162	1933 Long Beach	6.3	CI	DS	368	130	0.0671	0.0671	MMI = 7 - 9	24.6	PGV per Wald el al, 1999 eqn 2
1163	1923 Kanto	7.9	CI	LG	39.1	10	0.0488	0.0488	PGA = 0.31	11.6	PGV (c/s)=95xPGA per Wald Figs. 3&4
1164	1923 Kanto	7.9	CI	SM	570	214	0.0671	0.0671	PGA = 0.31	11.6	PGV (c/s)=95xPGA per Wald Figs. 3&4

Notes.

1. DI = ductile iron. AC = asbestoc cement. S = steel. CP = concrete pipe. MX = combined materials (I.e., mixed)

2. Size refers to pipe diameter. LG = Large (> about 12 inches) SM = small (≤ about12 inches).

3. DS = distirbution system (mostly small diameter, but some large diameter possible)

4. Repair rate is repairs per 1,000 of pipe

5. Modified Demand, PGA, inches / second. Peak Ground Velocity. Entry of "---" means that the data point was screened out for reasons cited in this table.

6. Wald et al ([1999] equation 2 is as follows: MMI = 3.47 log(PGV) + 2.35, where PGV is in cm / sec.

7. 1.07 x Rate modification is to account for repairs omitted from Toprak [1998] analysis due to lack of some atttributes, but the damage did occur

8. 0.83 x PGV modification is to adjust peak PGV value of two horizontal directions to average horizontal vale of two directions (for Northridge only)

9. Data point screened out due to possible PGD effects. For San Fernando, only point in the northeast part of the valley were screened out per Barenberg [1988] and NOAA [1973].

10. These entries had aftershocks of similar magnitude as the main shock. The data points were screened out as the amount of damage caused by each event cannot be differentiated.

Table A.1-2. Screened Database of Pipe Damage Caused by Wave Propagation

APPENDIX B.

SIMULATION PAGES

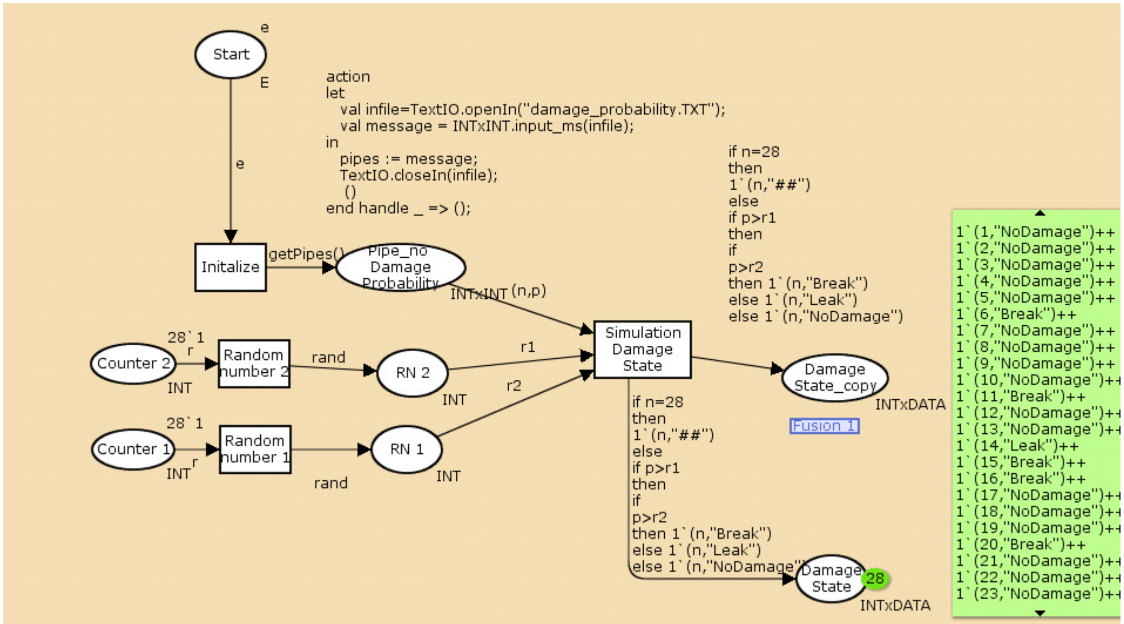


FIG.1. Simulation of Damage State

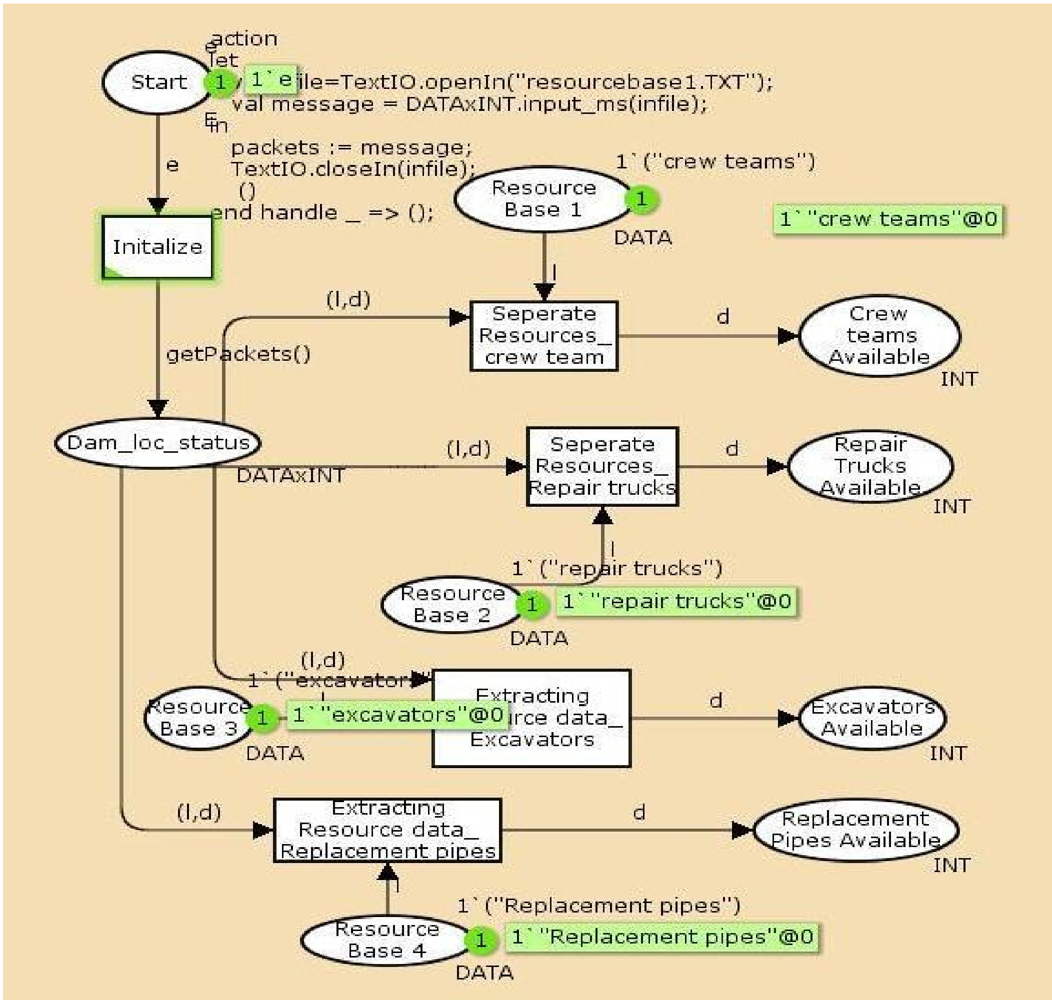


FIG.2. Available Resources Module

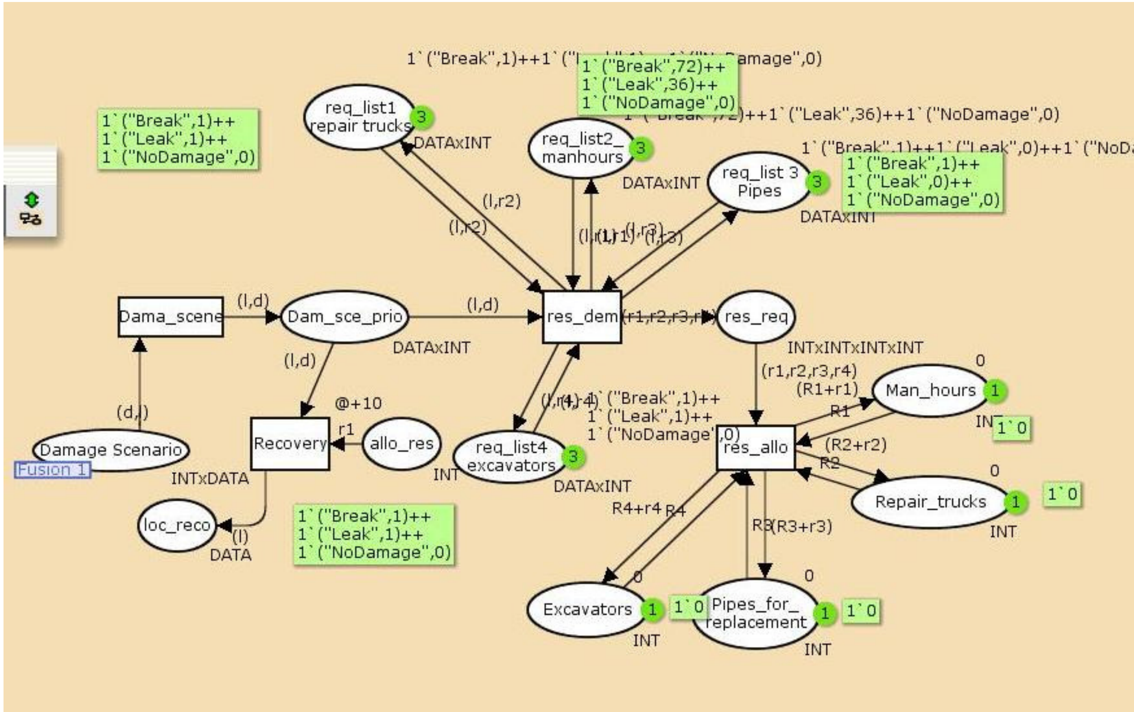


FIG.3. Estimation of Resources Required

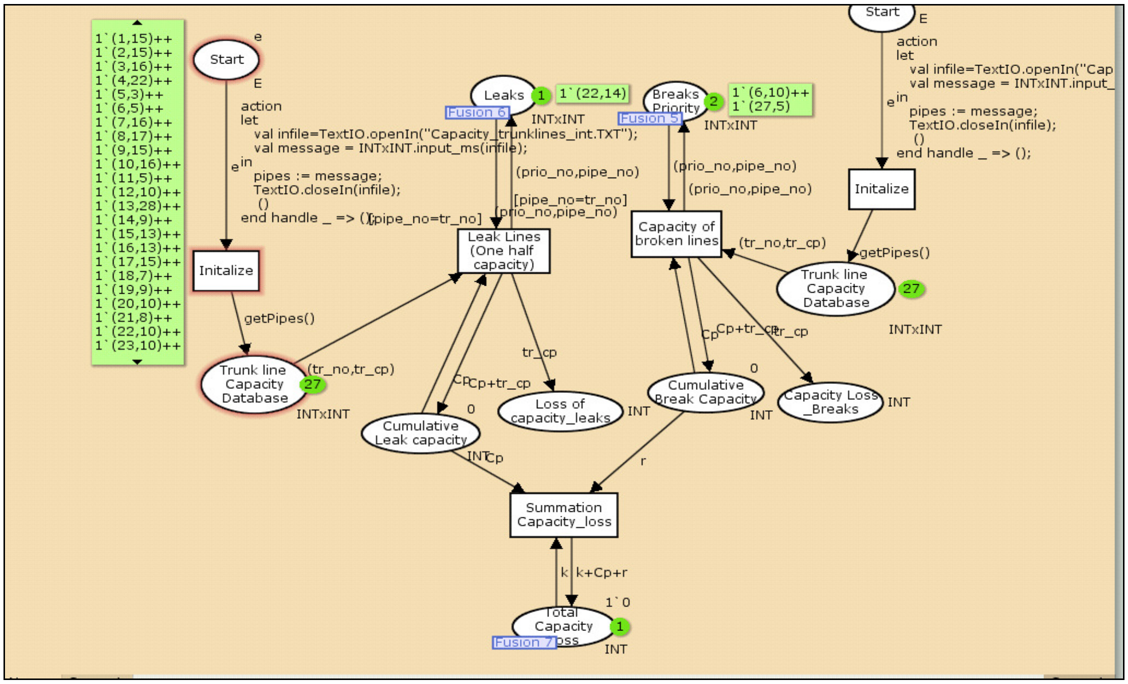


FIG.4 Calculation of the Total Capacity Loss due to Damages

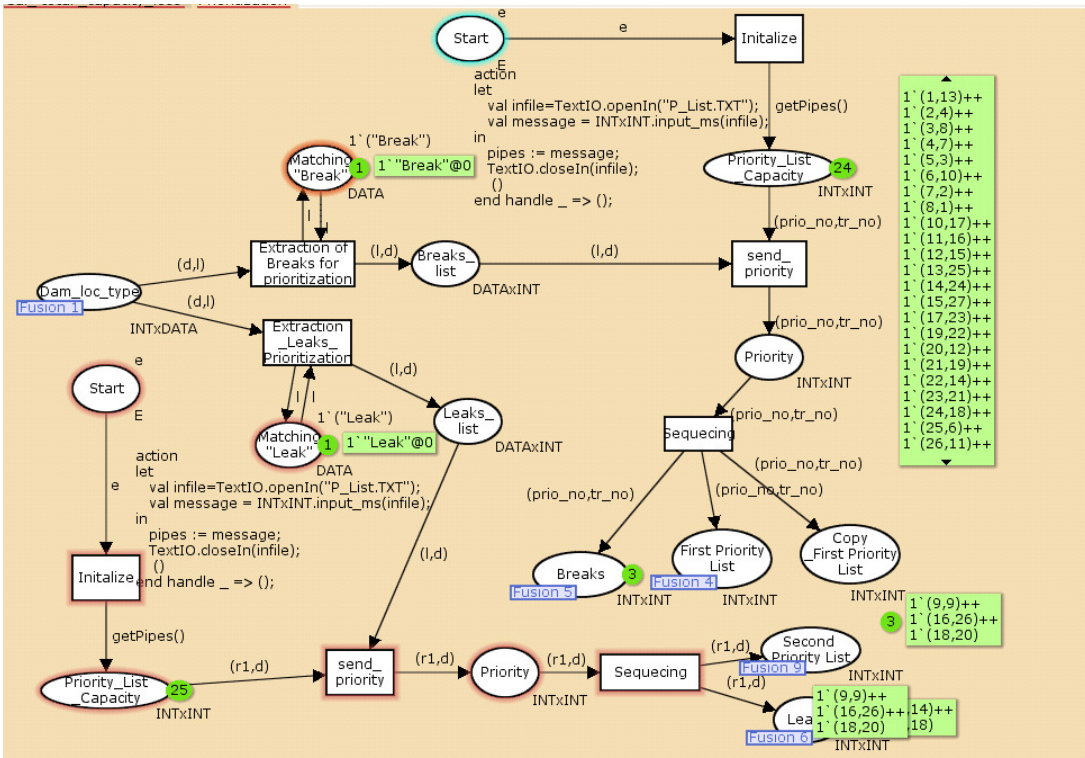


FIG. 5. Prioritization of Damages for Restoration

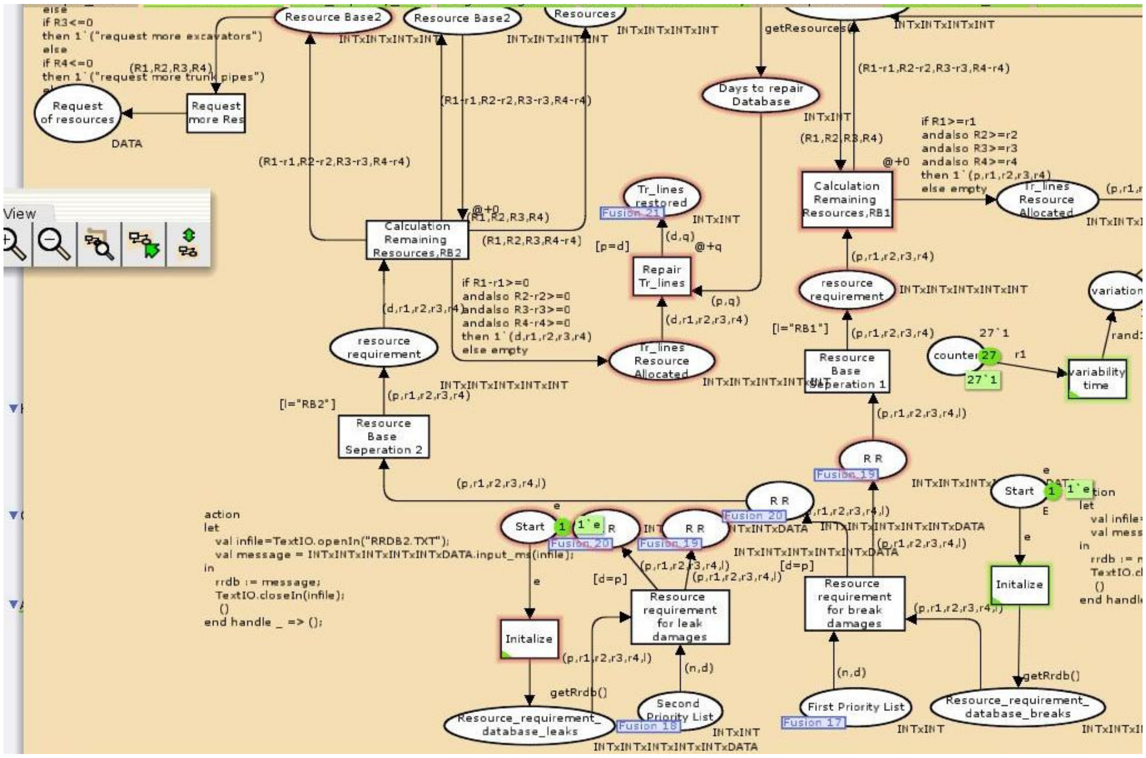


FIG. 6. Resource Allocation

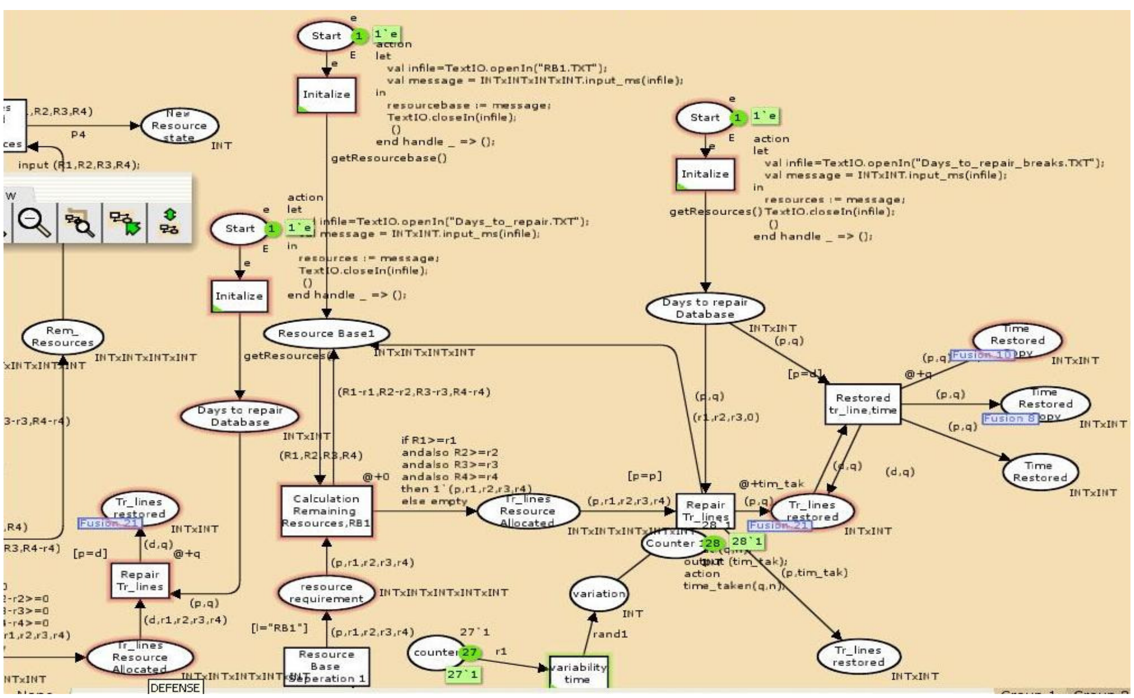


FIG. 7. Resource Allocation (conti.)

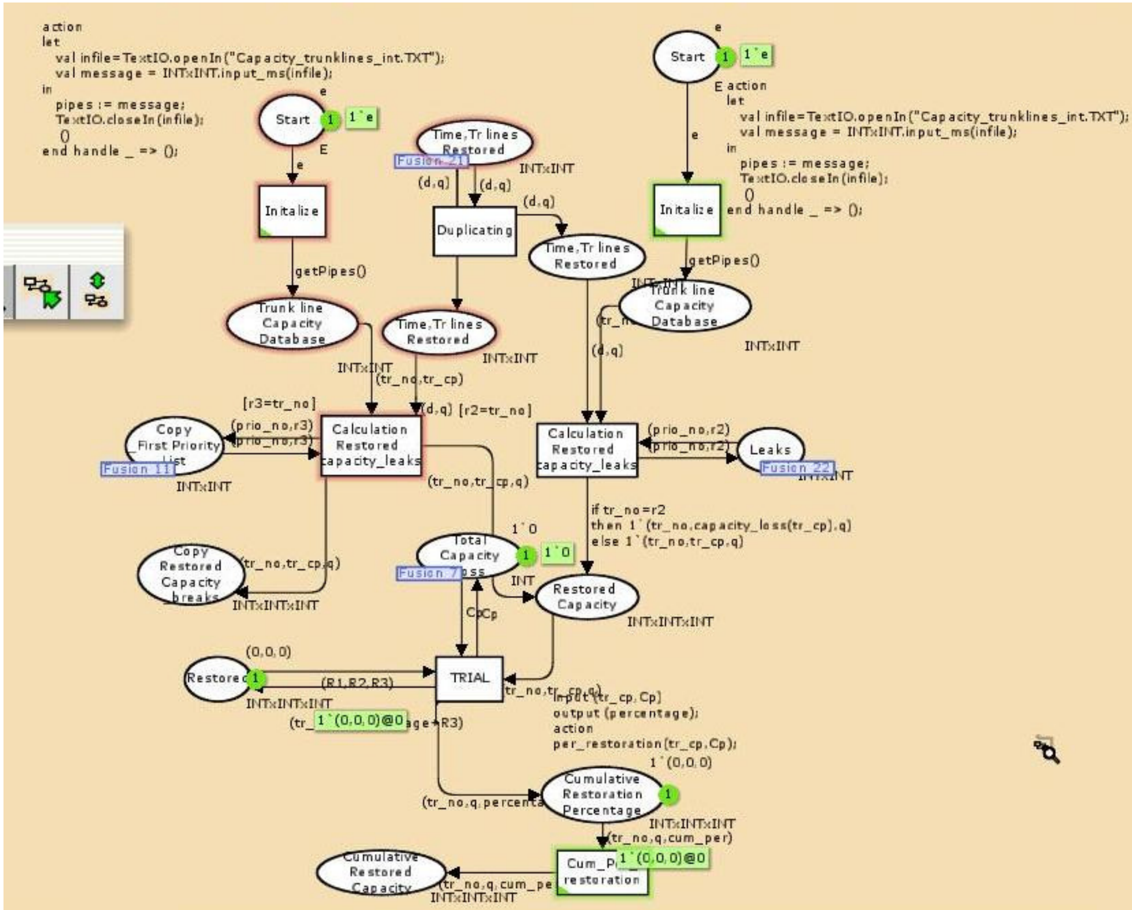
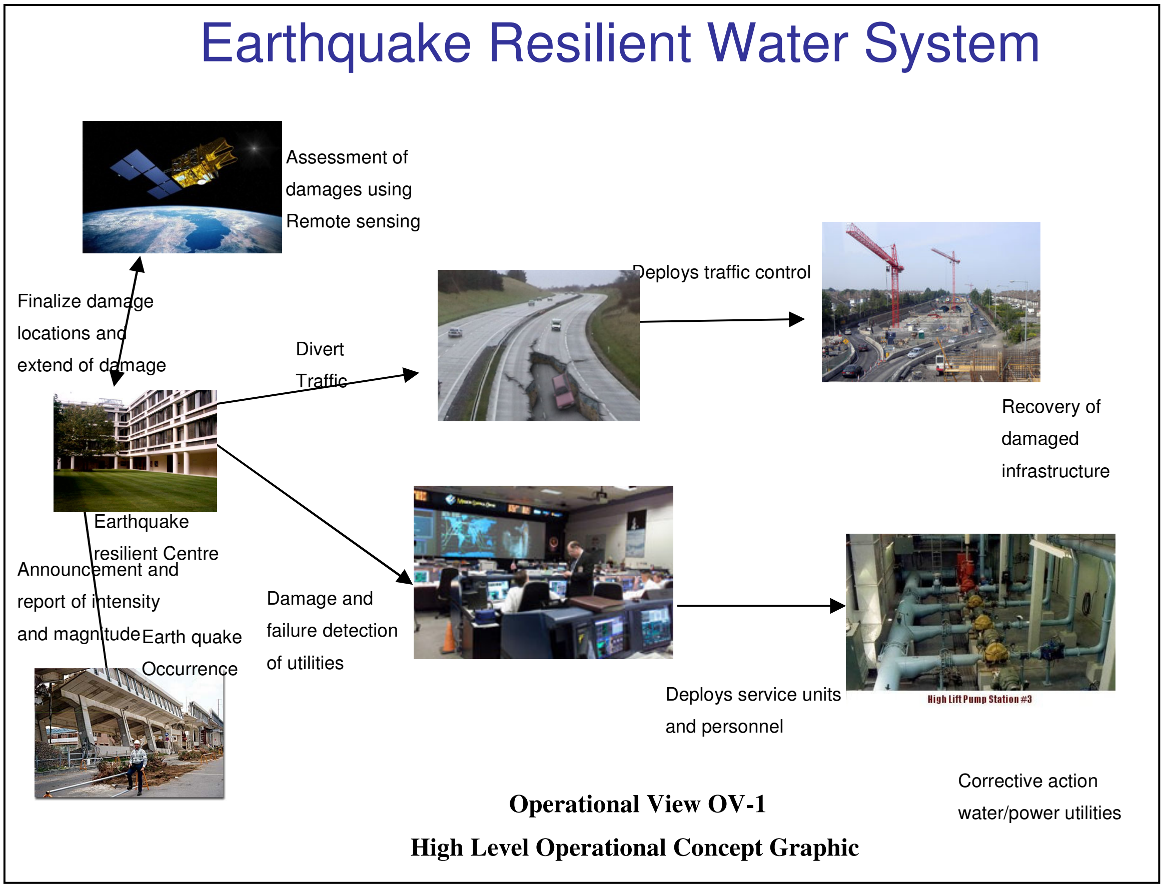


FIG. 8. Estimation of Restoration Progress

APPENDIX C

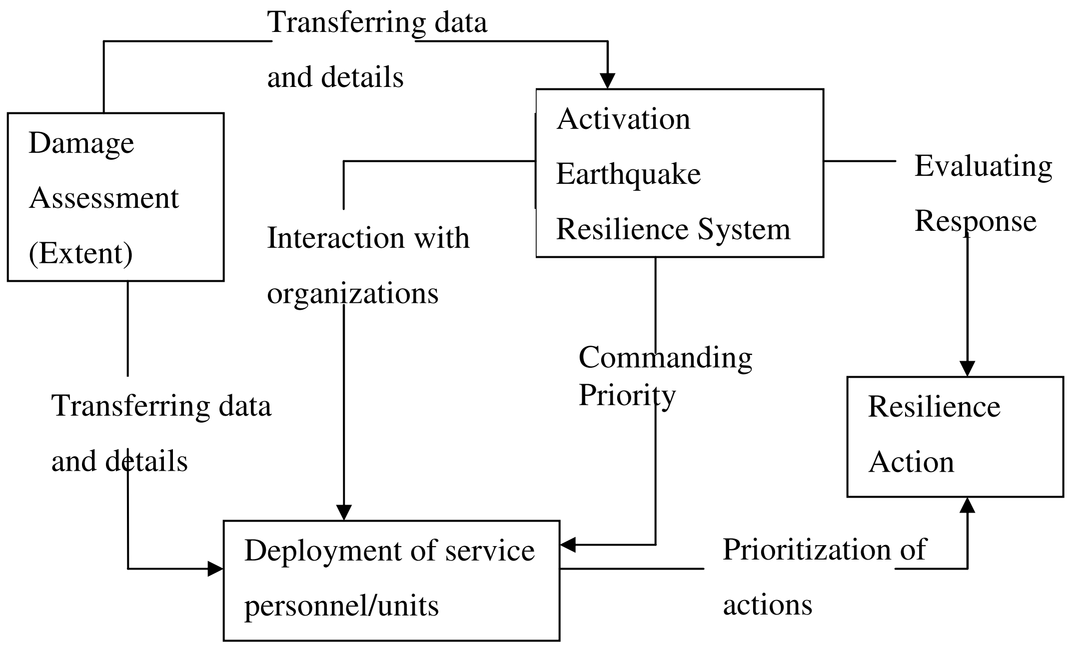
DEPARTMENT OF DEFENSE ARCHITECTURE FRAMEWORK (DoDAF)

DIAGRAMS



Operational View OV-1

High Level Operational Concept Graphic



Operational Activity Model OV-5 –System level

VITA

Nandini Kavanal Balakrishnan was born in Kerala, India, on November 25, 1980. She received her Bachelor of Technology degree in Civil Engineering from the National Institute of Technology, Calicut, India, 2003. After her graduation she joined Centre for Water Resources Development and Management, Government of Kerala. After working there for 16 months, she joined Marine Sciences Division of Centre for Earth Science Studies, an autonomous research wing under Kerala State Council for Science and Technology. Working on multiple projects in these organizations she decided to pursue her Masters in Systems Engineering. She joined the Department of Engineering Management and Systems Engineering at Missouri University of Science and Technology, Rolla, USA in Fall 2006 where she got an opportunity to contribute in the field of Infrastructure Systems. During this period the department recognized her work as outstanding for the year 2007-2008. Nandini is a student member of Earthquake Engineering Research Institute (EERI) and also a student of International Council of Systems Engineering (INCOSE).